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**A COMPARISON OF HEAD-UP AND HEAD-DOWN DISPLAY
FORMATS DURING INSTRUMENT FLYING TASKS**

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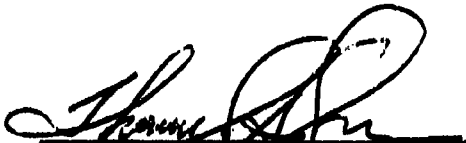
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13. ABSTRACT (Maximum 200 words) In March 1989, the Chief of Staff of the Air Force issued a study regarding the status of instrument flying within the Air Force. In that report, specific recommendations were presented, first of which was the necessity to develop a standardized HUD format suitable for use as a primary flight reference. Since that time a HUD symbology set was proposed and adopted conditional upon final validation as a primary flight reference. The present report documents the simulation phase of the validation process in which a total of 38 pilots participated. The validation of the symbology set consisted of a comparison of pilot performance data during three instrument flight tasks 1) Unusual Attitude Recovery, 2) Precision Approach, and 3) Precision Instrument Maneuvering. Results indicated that pilot data were significantly improved while flying with the HUD during the Precision Approach and Instrument Maneuvering tasks. During the Unusual Attitude Recovery tasks, no significant differences were demonstrated; however, the HUD symbology showed a trend toward faster reaction times, particularly for the nose low recoveries. Based on these results, the CSEF recommended initiation of the follow-on flight test phase of the validation process.				
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Executive Summary

Based on findings from a 1989 Air Force Chief-of-Staff commission on Instrument Flying, the Head-Up Display (HUD) is increasingly being used by pilots as a primary source of instrument flight information. Unfortunately, existing HUDs were not designed to serve in such a capacity. In fact, AFM 51-37 specifically states that current HUDs "do not provide attitude cues sufficient to enable the pilot to maintain full-time attitude awareness or recover from some unusual attitudes and therefore should not be used as the primary source of attitude information." However, due to the compelling appeal of the HUD as a primary flight reference, it is reasonable to assume that pilots will most likely continue to use the HUD in this manner. If in fact pilots are going to continue using the HUD as a primary attitude source, it is imperative that a set of HUD symbology, acceptable for use as a primary flight reference, be developed. Tasked by HQ Air Force, it became the responsibility of Air Force Material Command (AFMC) and the Instrument Flight Center (IFC) to develop and validate a standard HUD symbology set suitable for use as a primary flight reference.

Over the last 4 years, an extensive review of existing and proposed symbology was conducted resulting in the development of a proposed baseline symbology set which could potentially be used as a primary flight reference. This baseline was presented to a 1990 meeting of the Air Force Instrument Flight Working Group at which time the proposed baseline was adopted as an Air Force standard providing the successful completion of in-flight validation. AFMC and the IFC were tasked with the validation of this provisional HUD standard for use as a primary flight reference display. A technical team consisting of representatives from Aeronautical Systems Center, Wright Laboratory, Armstrong Laboratory, the Air Force Flight Test Center, and USAF IFC was established to determine the appropriate validation methodology.

Given that no existing objective criteria were available, the technical team decided that the HUD would be validated by determining whether pilot performance using the provisional HUD symbology favorably compared to that using existing head-down instrumentation. Therefore, it became the objective of this validation effort to 1) evaluate pilot performance differences between the "provisional" HUD symbology suite and a head-down instrument suite, and 2) collect subjective questionnaire data from operational fighter/attack and test pilots on the appropriateness of the symbology for instrument flight as well as identify any potential conflicts between the instrument flight symbology and other mission symbology or requirements.

As a cost savings and risk reducing measure, the technical team decided to conduct symbology integration and preliminary validation in the Crew Station Evaluation Facility's (CSEF) F-16 simulator prior to the flight test validation. Such an approach provided the opportunity to collect sufficient data to achieve statistical confidence without incurring the cost of a lengthy flight test program. In addition, if the simulator results were unfavorable, the flight test program could be terminated prior to committing significant funds.

During the Phase I simulation program 23 Air Force pilots flew three instrument flying tasks: 1) Unusual Attitude Recovery, 2) ILS Approach, and 3) Precision Instrument Maneuvering. Data collection was conducted in the CSEF's F-16 simulator using a Block 25 HUD driven by a Vector General symbol generator. All head-down instrumentation was actual F-16 hardware with the exception of an Attitude Directional Indicator (ADI) which replaced the F-16 Attitude Indicator. Upon completion of all data collection trial, subject pilots completed an extensive debrief survey which provided the opportunity to identify significant strengths or weaknesses in the HUD symbology.

Analysis of the Phase I data indicated that pilot performance on both the ILS Approach and the Precision Instrument Control task was superior to that flown with the head-down instrumentation. Data analyzed for the Unusual Attitude Recoveries showed no significant performance differences between the two display types. A review of the post data collection debriefs indicated that the pilots were comfortable with the symbology and its potential adoption as a primary source in instrument information. Based on these findings, the technical team decided that proceeding to flight test was justified.

As a result of this flight test program, issues regarding symbology format, symbology mechanization and evaluation procedures were identified which required resolution prior to final validation. These issues focused primarily upon the mechanization and format of the HUD's attitude reference. For this reason, a Phase II simulation effort was initiated. The objective of the Phase II effort was to integrate modifications to the symbology to resolve the deficiencies identified during the Phase I flight test and conduct a second simulation validation similar to that conducted during Phase I. A secondary objective of the Phase II program was to address the issue of mission compatibility. As a result, in addition to the three instrument tasks an air-to-ground mission was developed as a means of exercising the symbology in a limited mission role. Because the mission was flown merely for demonstration purposes, no objective data were collected.

Data collection was conducted much in the same manner as in Phase I. Fifteen Air Force pilots participated in the evaluation flying the same three instrument flown during the Phase I simulation. The procedure used for the unusual attitude task was modified based on findings resulting from the flight test program. Lessons learned from the flight test program stressed the importance of dynamic entry into the unusual attitude. Phase I trials were initiated with the aircraft in a static position at 0° AOA; therefore any effects due to aircraft dynamics would not have been demonstrated. As a result, all Phase II trials were initiated by having a robot pilot fly the simulator into the desired configuration at which time a start tone was presented, instructing the pilot to open his eyes and recover the aircraft.

The second modification to the methodology was the incorporation of crosswinds during the recoveries. Flight test pilots reported that the lateral movement of the CDM during the Phase I flight test was significantly aggravated by the presence of gusting crosswind. To ensure that such effects were demonstrated in Phase II simulation, variably gusting winds from 30 to 45 kts were incorporated into the simulation. The implementation of the robot pilot coupled with the incorporation of the crosswind model more closely approximated conditions experienced during flight testing.

Results of the data analysis again indicated that pilots' performance data flying with the HUD format for both the ILS Approach and the Precision Instrument Control Task was superior to that flown with the head-down instrumentation. Although the analysis for the Unusual Attitude Recoveries showed no statistically significant differences, there was a trend toward improved accuracy rates while recovering with the HUD for the nose-down recoveries.

BACKGROUND

In March 1989, HQ USAF released a report on the status of instrument flying standardization. The report was prepared for the Chief of Staff of the United States Air Force and included discussions and specific recommendations for standardization in cockpit development.

The report stated that "Recent instrument related flight mishaps are causing a growing concern about reduction in Air Force instrument flight capability. Expanding technology and more realistic mission training are enhancing our ability to accomplish the complex employment portion of our flying mission. Unfortunately, this improved "weapons on target" capability is not accompanied by a specific focus on basic instrument flight skills and overall instrument flight capability. This lack of emphasis, combined with overall lower pilot experience levels, is making our combat crews less capable of performing the instrument portion of their mission. The changes in cockpit design have created new problems as others were solved. A significant effort is needed to improve the current cockpit development process."

The report went on to identify several specific recommendations with regard to instrument flying standardization; the first of which was to establish a standard for USAF instrument flight symbology, terminology, and mechanization for both head-up (HUD) and head-down displays. The standard was to address the use of the HUD as a primary flight reference and the presence of a prominent, centrally located primary attitude display.

According to AFM 51-37 however, current HUDs "do not provide attitude cues sufficient to enable the pilot to maintain full-time attitude awareness or recover from some unusual attitudes and therefore should not be used as the primary source of attitude information." Therefore, the Air Force Instrument Flight Center (USAF/IFC) and Air Force Materials Command (AFMC) were tasked with the development and validation of a standard for HUD symbology.

In support of this tasking, the IFC and AFMC began an extensive review of existing and proposed HUD symbology being used both within the Air Force and Navy as well as in other military

agencies worldwide. As a result of this effort a baseline HUD symbology configuration was proposed which consolidated several symbology enhancements (Evans and Bitton, 1990).

During a December 1990 meeting of the Air Force Instrument Standardization Working Group, attended by representatives from each of the Air Force major commands, the baseline symbology set was adopted as a provisional Air Force standard for HUD symbology. AFMC and the IFC were tasked with the validation of this provisional HUD standard for use as a primary flight reference display. A technical team consisting of representatives from Aeronautical Systems Center (ASC/EN), Wright Laboratory (WL/XPK), Armstrong Laboratory (AL/VNEG), the Air Force Flight Test Center (AFFTC) and USAF IFC was established to determine the appropriate validation methodology.

Direction from the Instrument Standardization Working Group stipulated that prior to the "provisional" HUD's adoption as the Air Force standard, it must first be validated in flight. As a cost saving and risk reducing measure, the technical team decided to conduct symbology integration and preliminary validation in the Crew Station Evaluation Facility's (CSEF) F-16 simulator prior to the flight test validation. Such an approach provided the opportunity to collect sufficient data to achieve statistical confidence without incurring the cost of a lengthy flight test program. In addition, if the simulator results were unfavorable, the flight test program could be terminated prior to committing significant funds.

Due to the lack of specific performance criteria against which the HUD symbology could be evaluated, it was decided that the HUD would be validated by determining whether pilot performance using the provisional HUD symbology favorably compared to that using existing head-down instrumentation. Therefore, it became the objective of this validation effort to 1) evaluate pilot performance differences between the "provisional" HUD symbology suite and a head-down instrument suite, and 2) collect subjective questionnaire data from operational fighter/attack and test pilots on the appropriateness of the symbology for instrument flight as well as identify any potential conflicts between the instrument flight symbology and other mission symbology or requirements.

This report presents the results and recommendations from the overall simulation program. The simulation program was conducted in two phases. Phase I describes the results from the initial simulation effort that was designed to validate the provisional symbology as a primary flight reference. Phase II was initiated due to deficiencies identified during the follow-on flight test program. These deficiencies were further investigated and were brought to resolution prior to initiation of the second phase. Phase II describes these deficiencies, the proposed solutions as well as the results and conclusions.

PHASE I METHOD

Apparatus

Crew Station Evaluation Facility. The study was performed at the CSEF, an Air Force simulation facility that is managed by the Crew Station and Human Factors Section (ASC/ENECS) in the Crew Systems Branch (ASC/ENEC). The branch is part of the Support Systems Engineering Division (ASC/ENE) contained within the Directorate for Integrated Engineering and Technical Management (ASC/EN). The facility supports System Program Offices and other Air Force laboratories in their acquisition engineering through pilot vehicle interface evaluations using man-in-the-loop simulation. Currently, the CSEF has the capability to perform full and part mission simulations for a variety of aircraft including the F-16, F-111, F-22, and KC-135.

F-16 Simulator. The CSEF F-16C simulator was used during this study (see Figure 1). The simulator was constructed using a salvaged single-seat F-16 cockpit, truncated in front of the forward portion of the windscreen, and approximately 57 inches behind the canopy hinge. The undercarriage was removed, and the floor panel section sat on small canister-type wheels. The simulator did not employ a motion base. The cockpit controls and displays were configured to the F-16C Multi-National Staged Improvement Program (MSIP) Block 30 design that included two 4x4 inch monochrome MultiFunction Displays (MFDs), an Integrated Control Panel (ICP), a Data Entry Display (DED), Hands-On Throttle and

Stick (HOTAS) controls, centralized flight instruments and Block 30 avionics suite. The side control stick, throttle, a Block 25 Head-Up Display with a 20 x 16 degree instantaneous field-of-view and a 25 x 25 total field-of-view, and flight controls were actual F-16 components. The only modification to the F-16 flight instruments was the replacement of the primary Attitude Indicator (AI) with a flight director equipped Attitude Directional Indicator (ADI). All other instruments, controls, and displays were simulated using locally available equipment. A photograph of the cockpit including all head-down instrumentation is shown in Figure 2.

External Visual Scene Generation. An IMAGE IIIT Visual System was mounted directly in front of the F-16 simulator. The IMAGE IIIT system presented collimated computer generated imagery representing the outside world to the pilot. Three monitors presented a contiguous 120° visual scene directly in front of and to the left and right of the pilot's seated position. The IMAGE IIIT system had the capability to provide a variety of special effects including weather, time of day, continuous terrain (linked data bases), texture, and airfield lighting.

HUD Graphics Generator. The HUD symbology was generated using a Vector General symbol generator, while a PDP 11/34 computer mapped and controlled the HUD's position. Gould 32/7780 and 32/8730 mainframe computers sent the flight parameters to the PDP computers to enable it to position the stroke symbology so the pilot can use the HUD to fly the simulator.

Experimenter's Console. The experimenter's console (See Figure 3) included a complete intercom system for up to four test engineers/observers and the pilot. The console duplicated all electronic displays (HUD, MFDs, DED, etc.) and provided "quick-look" feedback on pilot performance. From the console, the test engineer controlled simulator operation and selected appropriate test parameters (test subject number, test conditions, etc.).

Baseline Head-Up Display. During a December 1990 meeting of the Instrument Standardization Working Group a basic instrument standard was drafted to govern the development and validation of basic flight instruments. It was to these requirements that the present baseline HUD symbology was designed. They are as follows:

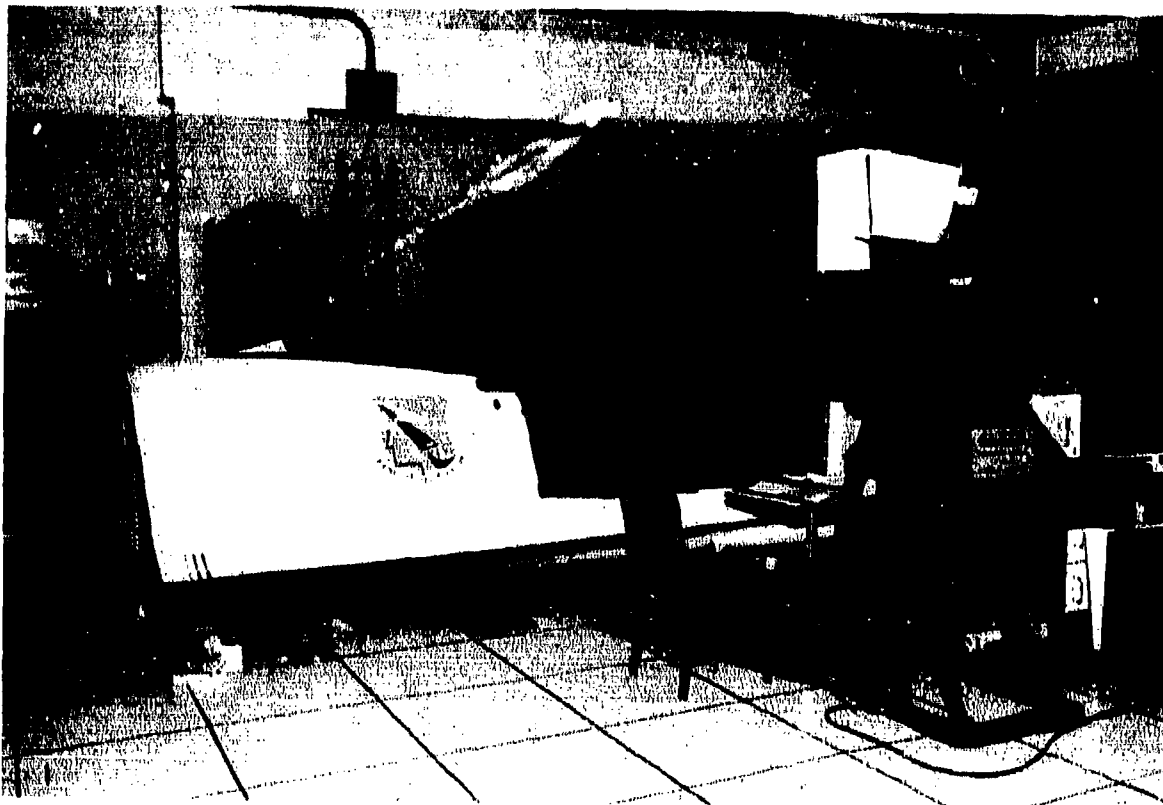


Figure 1. CSEF F-16 Simulator

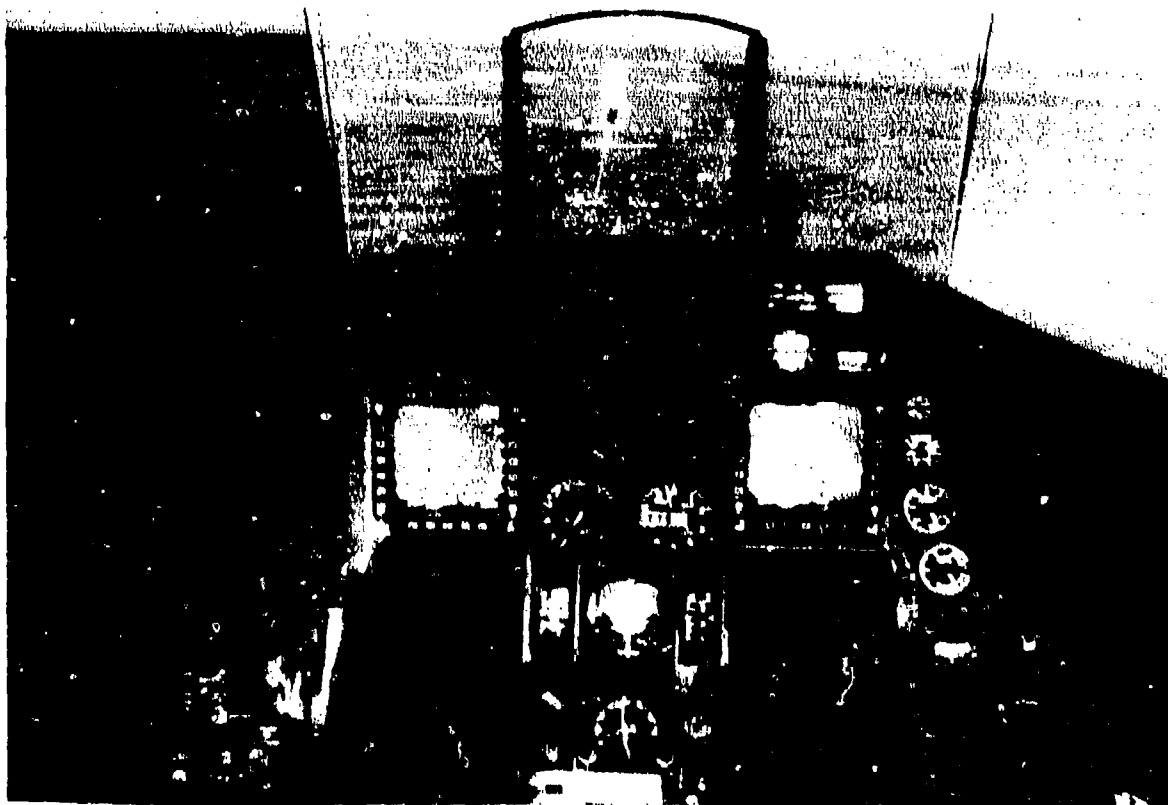


Figure 2. F-16 Cockpit Instrumentation



Figure 3. Experimenter Console

a) **Basic Standard:** Primary flight instrumentation must always be present and must provide full-time attitude, altitude and airspeed information; an immediately discernible attitude recognition capability; and unusual attitude recovery capability; and unambiguous and complete fault indications.

b) The elements of information which support the basic standard must be positioned and arranged in a manner which enables the pilot to perform a natural crosscheck.

c) Elements which support the basic standard will be standardized in terminology, symbology, mechanization and arrangement.

d) For a single medium display (e.g., head-up or head-down multifunction display) to solely satisfy flight instrumentation requirements, it must adhere to the basic standard and will always display climb/dive angle (or pitch and vertical velocity) bank angle, barometric altitude, indicated/calibrated airspeed and a prominent horizon.

There are several features of the present HUD that were designed specifically to respond to one or more of the above requirements. The following is a brief review of the significant features of the baseline HUD symbology suite and their intended contribution to the compliance of the basic instrument standard.

Climb/dive marker (CDM). As the 1989 Instrument Standardization Working Group Study reported, pilots have become accustomed to using the HUD as a primary flight reference. One of the fundamental benefits of the HUD, and therefore one of the reasons it has achieved such wide use as a primary reference, is the presentation of the velocity vector as the primary control reference. Using traditional pitch referenced displays requires the pilots to integrate their pitch attitude, vertical velocity and angle-of-attack to determine aircraft flight path. The incorporation of the flight path marker (FPM) has eliminated the need for these mental gymnastics by indicating where the aircraft is going rather than where it is pointed (i.e., pitch attitude). Although few would argue that flight path is a more intuitive reference for precise flight path control, it does have some deficiencies that have, in part, prohibited the adoption of the HUD as a primary flight reference display by the Air Force.

One feature of existing HUDs that has contributed to the hesitance by the Air Force to adopt it as a primary flight reference is the lack of stability of the flight path marker. The FPM, unlike the fixed pitch reference, is much more dynamic within the HUD field-of-view (FOV). These dynamic effects are caused in the horizontal axis by drift due to crosswinds and sideslip due to pilot induced yaw, and in the vertical axis by the inertial lags resulting from transient motion responses to flight control inputs. This resultant lag in the velocity vector causes a displacement of the FPM within the FOV of the HUD. During highly dynamic maneuvering, this displacement can often render the FPM useless as a control reference.

For example, the displacement of the FPM can cause two undesirable effects. First, the displacement of the FPM also displaces all the symbols that are positioned relative to the FPM (i.e., ILS/TACAN symbology, Climb/Dive Ladder). The motion and displacement of the symbols make the HUD symbology more difficult to read. Secondly, the displacement of the FPM by the transient AOA may cause the pilot to overshoot a desired climb-dive angle which may result in pilot induced oscillations as he attempts to reacquire.

Two features were incorporated into the provisional HUD to compensate for the dynamic characteristics of the FPM in both the vertical and lateral axes. Caging of the FPM eliminated the lateral displacement of the control reference from the center-line of the HUD caused by excessive beta angles while quickening reduced the vertical displacement of the FPM caused by aircraft inertia during aircraft maneuvering.

Caging. Caging is a means by which the lateral displacement of the FPM is restricted to eliminate the adverse effects of large beta angles caused by excessive crosswinds or sideslip. The concept of the caged FPM, hereafter referred to as the Climb/dive marker (CDM), as the primary control reference is not a new idea as many current aircraft including F-16 and F-15 incorporate a similar feature called drift cutout. The benefit of the CDM and drift cutout is that it stabilizes the primary flight symbology within the lateral axis of the HUD by removing the effect of beta (i.e., drift due to winds or sideslip).

The major drawback to using a strictly caged CDM as the aircraft control reference is that

pilots have found when using a flight path marker they could place the control reference over a position in space to be assured that the aircraft would fly through that space. A compromise between display stability and conformality was achieved by incorporating a CDM, to which the climb/dive ladder (i.e., pitch ladder) is referenced and a velocity vector symbology that remains conformal to the outside world.

Once we decided to incorporate a CDM referenced display, a second compromise had to be achieved. If the CDM is to remain fixed on the vertical centerline of the HUD thus allowing no lateral movement of the symbol, conformality between the HUD horizon line and the real world horizon line cannot be maintained during high-drift/high-bank angle maneuvers. The compromise solution was to allow slight lateral movement of the CDM to maintain full-time horizon correlation. The specific mechanization implemented was such that the amount of the lateral displacement became a function of the magnitude of the beta angle, bank angle, and angle-of-attack such that maximum deflection was achieved when the beta angle, bank angle and angle-of-attack were all high.

Quickening. To overcome the problem of vertical instability, the position of the CDM was "quickened." The goal of "quickening" was to filter out the transient AOA caused by inertial lags. Take for example, a situation where the pilot is on approach and is below the desired glideslope. The pilot makes an appropriate nose-up correction to reduce the rate of descent. Initially, both the ladder and CDM will dip downward in the display reflecting the pitch attitude change resulting from the control input. This is not a delay in the display but rather the effect of aircraft inertia causing flight path to lag instantaneous changes in pitch attitude. Once the pilot achieves the desired pitch attitude and terminates the control input, the CDM, overcoming the effect of inertia, continues to rise stabilizing approximately one second after the control input was terminated. Under such conditions, the pilot is required to lead the CDM to achieve the desired flight path angle and prevent control overshoots. If the pilot fails to lead compensate the CDM, he or she becomes susceptible to pilot induced oscillation and potential loss of situational awareness.

Evaluations conducted by the Naval Air Test Center concluded that during approach and landing, a washed-out pitch attitude lead term results

in superior performance while a pitch rate lead term is more appropriate for the highly dynamic maneuvers occurring during up-and-away flight (Huff and Kessler, 1989).

Climb/Dive Ladder. Two other inherent problems with using the HUD as opposed to a conventional ADI as a primary source of attitude information are 1) the limited field of view of the HUD, and 2) the lack of contrast provided by the climb/dive ladder in representing positive and negative climb/dive angles. Ladder compression and formatting techniques were developed in an attempt to counter these inherent weaknesses.

Ladder compression. A conventional ADI provides the pilot +/- 45 degrees of attitude reference on either side of the pitch reference symbol, some EADIs are capable of +/- 90 degrees. At best, current HUDs are capable of providing +/- 13 degrees of climb/dive reference. The effect is the same as if the pilot were looking at the ADI through a straw; at high pitch rates, the lines of the climb/dive ladder pass through the HUD FOV so fast that timely interpretation of aircraft attitude is near impossible.

In an attempt to "slow down" the rate at which the climb/dive ladder passed through the HUD, the ladder was compressed. Historically, the climb/dive ladder has been drawn conformal to the outside visual scene meaning that the 10° line overlies a point 10° above the horizon. The incorporation of compression, however, caused the ladder to lose conformality with the outside visual scene. In order to maintain conformal with the outside visual scene, the compression ratio of the ladder was mechanized to change as a function of climb/dive angle such that the ladder was not compressed, or 1:1 ratio with the outside visual scene, from 0 to +/-5 degrees and increased linearly to 4.4:1 ratio with the outside visual scene at the zenith and nadir. Therefore, the ladder remained conformal about the horizon, maintaining conformality during ground referenced flight such as approach and landing and low level navigation, and compressed at larger climb/dive angles where outside correlation was not a high priority. A detailed description of the compression algorithms is provided in Appendix A.

Ladder format. The second limitation of the HUD in providing sufficient attitude reference was its lack of contrast between positive and negative climb/dive

angles. In an attempt to maximize hemispheric asymmetry, several techniques were adopted.

a) The most universally accepted technique was to dash the ladder lines in the lower hemisphere while the upper hemisphere lines remain solid.

b) A second technique adopted was bending the positive ladder lines half the climb/dive angle the line represents (Example: the 20° climb/dive line was articulated at 10° relative to the horizon). At higher climb/dive angles, the lines formed a funnel pointing toward the horizon; this effect was enhanced by placing the tabs on the inside of the ladder lines. This technique not only provided asymmetry between hemispheres, but also a sense of relative magnitude of climb (e.g., the greater the articulation, the greater the climb angle). This approach has shown promise in previous research; however, there remains some concern regarding the potential loss of gross roll perception caused by the articulation of the ladder lines (Ward and Hassoun, 1989; Weinstein and Ercoline, 1990). For this reason, articulation was incorporated only on the positive climb/dive lines. This decision was based on the argument that if an error in roll assessment were to occur, it is less critical if it occurs during a steep climb as opposed to a steep dive.

c) A third technique adopted was the tapering of the dive ladder lines so that the lines got shorter as the dive angle they represented got larger. This approach had the same advantage as articulation without the potential roll confusion often associated with articulation. For these reasons, tapering was incorporated for the negative climb/dive lines.

The combination of the ladder articulation for the positive lines and tapering for the negative served to further enhance the asymmetry between up and down. In addition, the magnitude of bend or taper provided a gross indication of the severity of climb or dive.

Ladder Numbering. Traditionally, flight path ladders numbers are placed on both sides of the ladder. This was required because the drift of the flight path marker often caused one side of the ladder to drift outside the FOV of the HUD. When flying a quickened and caged CDM, the ladder did not drift away from the center of the HUD, thus eliminating the requirement to number both sides of

the ladder. Furthermore, placement of ladder numbers on only the left side of the ladder provided an additional cue to roll orientation; if the numbers were on the right, the aircraft was inverted; if numbers were on the left, the aircraft was upright.

The baseline HUD symbology implemented for Phase I is presented in Figure 4.

Subjects

A total of 23 volunteer pilots participated as subjects in the simulator validation effort. Pilots participating in this study included three test pilots from the Air Force Flight Test Center, one IFC pilot and 19 TAF pilots. A brief review of the number and flying experience of the pilots who participated in the evaluation is provided in Table 1.

Table 1. Subject pilot experience

Aircraft	No of pilot	Avg HUD Experience (hrs)
F-16	8	665
A-10	6	855
F-15	7	940
A-7	4	930
Total	23	930

Procedure

Instrument Flying Tasks. Three flight tasks were developed for the evaluation, each designed to require extensive use of the information presented via the symbology sets. The three tasks included (1) unusual attitude recovery, (2) precision approach, and (3) precision instrument control.

Unusual Attitude Recovery. The primary concern regarding the adoption of the HUD as a primary flight reference is its ability to effectively provide the pilot with clear and unambiguous aircraft attitude information. Many of the weaknesses attributed to the HUD stem from its lack of sufficient cues for attitude referencing. The unusual attitude recovery task was included in this evaluation as a means of assessing the pilot's ability to rapidly assimilate and correctly act upon information presented in a head-up format.

Each unusual attitude recovery trial began with the pilot's eyes closed and the throttle set to a mid-range position. The simulator was set to one of the 12 initial conditions listed in Table 2. When the pilot was ready, the experimenter would initiate the

trial. Upon initiation, a tone was presented to the pilot through the headset, after which the pilot would open his eyes and recover the simulator.

Due to limitations with the follow-on flight test aircraft, and our desire to maintain consistency between flight test and simulator procedures, the pilot was instructed not to exceed the maximum of 4.0 Gs during the recovery. A variable frequency tone was presented to the pilot during the recovery to assist in awareness of the G limit. A 5-Hz tone was presented at 3.0 Gs, a 10-Hz tone for 3.5 Gs, and a solid tone was presented if the 4.0 G limit was exceeded.

The trial auto-terminated once the pilot achieved and maintained level flight for 5 consecutive seconds. Level flight was defined as $\pm 5^\circ$ gamma and $\pm 8^\circ$ roll. Upon termination, the HUD symbology was blanked or the head-down attitude reference was reset to a 0/0 condition.

Pilots were instructed to use AFM 51-37 procedures during the recovery from unusual attitudes. Back pressure on the stick was not to be applied until a positive lift vector had been achieved (i.e., aircraft was within 90° of the horizon). The pilot was further instructed on the use of the throttle during the recovery. If initial conditions had the aircraft in a nose-high condition and below 300 knots, the correct throttle input was to full mil-power. If initial conditions had the aircraft in a nose-low configuration and above 300 knots, the correct throttle input was to idle. Otherwise, throttle could be maintained at the middle position (i.e., 80% power setting).

Table 2. Unusual Attitude Conditions

Unusual Attitude	Pitch	Roll
1	-60	-135
2	-60	0
3	-60	60
4	-30	-90
5	-30	-45
6	-30	150
7	30	-135
8	30	-60
9	30	90
10	60	0
11	60	45
12	60	120

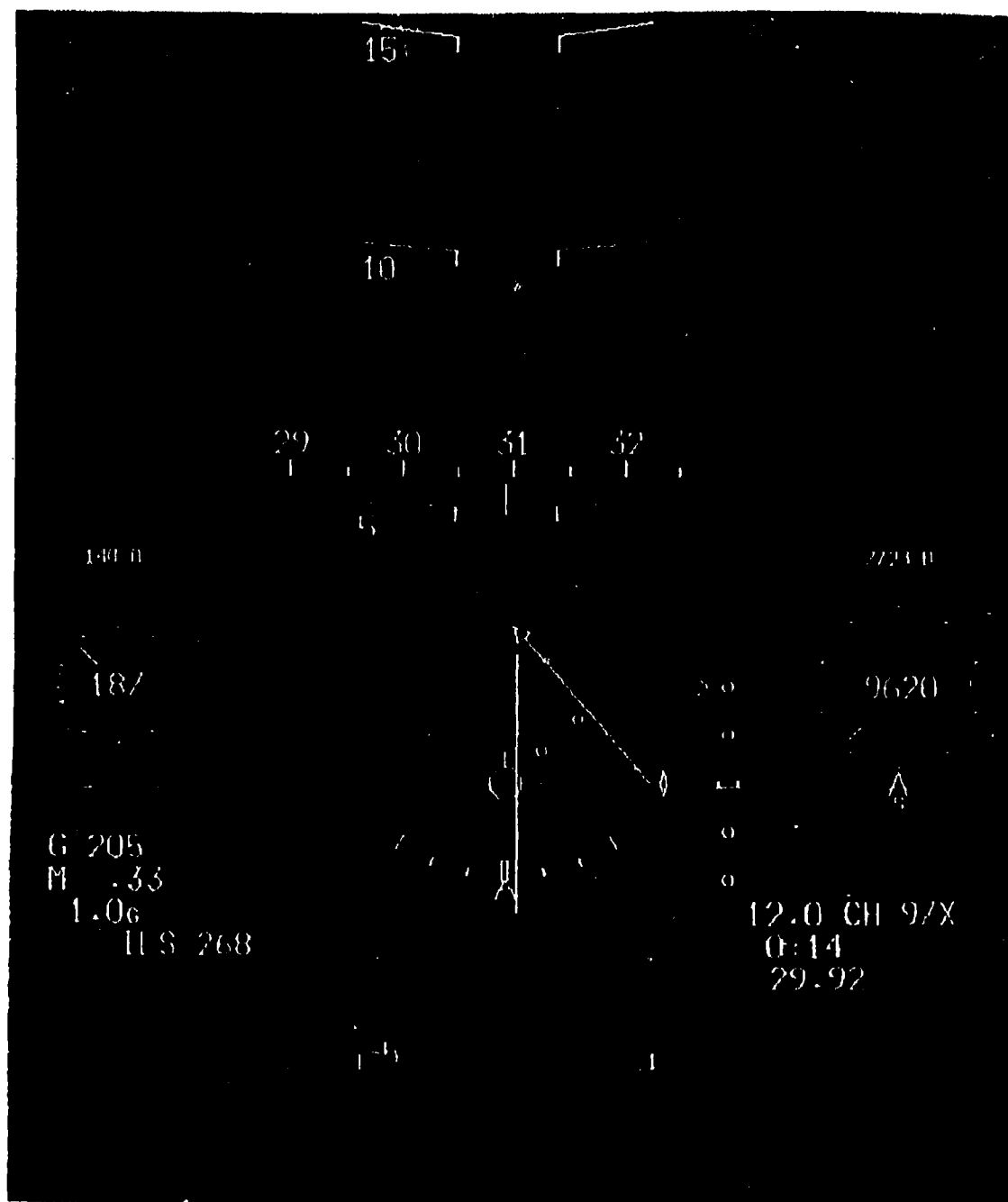


Figure 4. Baseline HUD Symbolry

Precision Instrument Control Task. The Precision Instrument Control Task (PICT) consisted of a series of instrument maneuvers requiring the pilot to maintain precise control over various flight parameters. Each trial began with the simulator established at level flight at 8400 ft, 250 knots, and a heading of 255°. Upon initiation by the experimenter, the simulator was taken out of reset and placed in position freeze mode which enabled the pilot to trim the aircraft without changing horizontal position. On the pilot's mark, the simulator was taken out of the position freeze mode and data collection began. The pilot was verbally instructed by the experimenter to complete a series of scripted instrument maneuvers. Following each instrument maneuver, the pilot was to maintain level flight for a period of 15 seconds prior to initiation of the next maneuver. The task consisted of a total of 11 segments as depicted in Figure 5.

Pilots were instructed to perform all climbs and dives at 3° flight path angle. All decreases in airspeed were to be conducted at idle power while all increases in airspeed were to be conducted at the discretion of the pilot.

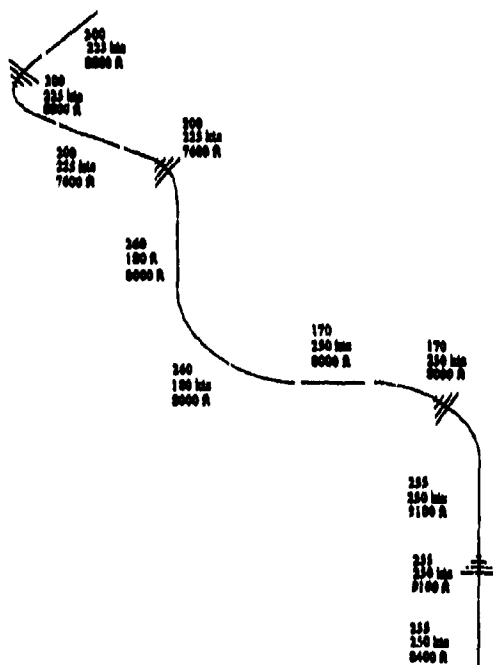


Figure 5. Precision Instrument Control Task.

ILS Approach. Upon release of the simulator by the experimenter, the pilot was instructed to trim the aircraft to establish himself on initial altitude, airspeed and heading conditions (i.e., 9500ft, 190kts

and 315°) which positioned the simulator for a 45° intercept of the final approach course of 268° at a DME of 12.8 miles. Once the pilot had trimmed the aircraft, data collection was initiated by pressing the cursor control switch on the throttle. The pilot was instructed to maintain initial altitude, airspeed and heading until the flight director began commanding a left turn to intercept the final approach course. Upon initiating the turn to the approach course the pilot was instructed to establish an approach airspeed of 140 kts prior to glideslope intercept. The pilot then flew the flight director to decision height at which time he would again press the cursor control switch to terminate data collection.

In order to increase the difficulty of the task, six wind gust models were developed. At various points throughout the profile the wind models would orchestrate changes in both magnitude and direction of wind, thus simulating wind shear condition. Wind direction varied from 0 to 360 degrees, while wind velocity varied from 0 to 15 knots. Wind models were randomly assigned to individual data trials.

Pilot Training. Upon arrival, each pilot participated in a 2-hour classroom training session. Included was a detailed description of the geometry, functionality and mechanization of the HUD symbology and some suggestions regarding specific strategies on how the symbology might best be used. Additionally there was a description of each of the three tasks to be flown during the evaluation.

After the classroom instructions, a brief test was administered to ensure the pilots' understanding of the symbology, tasks, and objectives of the evaluation. Each pilot then flew the simulator to gain experience with both the functionality of the symbology and the instrument flying tasks. Pilots continued training flights until an acceptable level of proficiency had been achieved, and the pilots felt comfortable with their understanding and use of the symbology. Performance was monitored from the experimenter's station. Total training time in the simulator for each pilot lasted approximately 3 hours.

Data Collection Sessions. Each pilot flew a total of six 45-minute sessions. Each session consisted of a block of 12 unusual attitude recoveries, a precision approach, a second block of 12 unusual attitude recoveries, and concluding with the precision

instrument control task. Pilots completed the six data collection sessions over the course of 3 days.

Data Collection

The primary objective of this evaluation was to compare pilot flying performance data between the provisional HUD symbology standard and a traditional electro-mechanical head-down instrument suite. Several dependent objective measures were collected and analyzed for each of the three experimental flying tasks. The following paragraphs describe these measures:

Unusual Attitude Recovery. Two dependent performance measures were collected during unusual attitude recovery tasks: 1) reaction time (defined as the time from trial initiation to first correct control input by the pilot), and 2) accuracy of the initial lateral stick input (roll/pitch) by the pilot.

Precision Instrument Control. The Precision Instrument Control Task was segmented into 11 phases. The definitions of these 11 phases are provided in Table 3. During these phases, five dependent measures were collected: 1) heading, 2) altitude, 3) airspeed, 4) bank angle, and 5) flight path angle. For each of these variables, Root Mean Square (RMS) values were calculated for all appropriate profile segments.

ILS Approach. The Precision Approach task was segmented into five phases. A definition of these five phases is provided in Table 4. During the dogleg and approach phases five dependent measure were collected: 1) heading, 2) altitude, 3) airspeed, 4) glideslope deviation, and 5) localizer deviation. For each of these variables, RMS values were calculated for all appropriate profile segments.

Table 3. Precision Instrument Control Task Phase Recognition Logic.

Phase	Begin	End
I	Pilot Mark	Phase I begin + 1 s
II	PA > 3 for 3 s	1,600 ft
III	Alt > 1,600 ft for 3 s	Phase III begin + 1 s
IV	Bank > 31 and PPA < 3 for 3 s	1,300 ft or Hda 175
V	Alt < 1,600 ft/Hda < 175 for 3 s	Phase V begin + 1 s
VI	Bank > 31 for 3 s	Hda 335
VII	Hda > 335/Alt < 1,600 for 3 s	Phase VII begin + 1 s
VIII	Bank > 31 and PPA < 3 for 3 s	7,700 ft or Hda 295
IX	Alt < 7,700 ft/Hda < 295/Alt > 215 for 3 s	Phase IX begin + 1 s
X	Bank > 31/PPA > 3 for 3 s	1,600 ft or Hda 295
XI	Alt > 1,600 ft/Hda > 295 for 3 s	Phase XI begin + 1 s

Table 4. Precision Approach Phase Recognition Logic.

Phase	Begin	End
I	Pilot Mark	Within 4 deg of localizer
II	Phase I end	Within 1/2 deg of localizer
III	< 1/2 deg left for 3 s	Range = 38,160
IV	Range = 38,160 ft	Pilot Mark

Pilot Questionnaires

At the conclusion of data collection, each subject pilot was asked to complete a debrief questionnaire. A copy of the questionnaire given to the pilots is provided in Appendix B.

PHASE I RESULTS

A review of the performance data means for each of the flying tasks performed during the evaluation is provided in Table 5. A $p < 0.05$ level was used as a criterion for rejecting the null hypothesis.

Unusual Attitude Recovery

Data collected during the unusual attitude recovery task included reaction time to first correct control input, and accuracy of initial control input. Pilots' reaction time and error rate data were analyzed using two one-way repeated measures Analyses of Variance (ANOVA). The first ANOVA compared two display conditions (HUD vs. HDD) for nose-up unusual attitude recoveries. The second compared the same two display conditions for all nose-down unusual attitude recoveries. Neither of the analyses indicated the presence of a significant difference between the two display conditions for either reaction time or error rate.

Precision Instrument Control

One-way repeated measures ANOVAs were conducted to identify pilot performance differences between the two display conditions, head-up and head-down, during the precision instrument control task. Results indicated a statistically significant main effect for display type with pilots performing better when using the HUD over the HDD for RMS Altitude Deviation, $F(1,22)=16.59$, $p < 0.0005$; RMS Airspeed Deviation, $F(1,22)=97.13$, $p < 0.001$; RMS Flight Path Angle, $F(1,22)=96.57$, $p < 0.0001$; and RMS Heading Deviation, $F(1,22)=19.01$, $p < 0.0003$.

ILS Approach

One-way repeated measures ANOVAs were also conducted to identify pilot performance differences between the two display conditions, head-up and head-down, during the ILS approach task. The results of the analysis indicated a statistically significant performance enhancement when using the HUD over the HDD for RMS Altitude Deviation, $F(1,22)=51.81, p<0.0001$, RMS Airspeed Deviation, $F(1,22)=6.82, p<0.016$, RMS Glideslope Deviation, $F(1,22)=26.58, p<0.0001$, RMS Localizer Deviation, $F(1,22)=23.89, p<0.0001$.

Table 5. Mean results of performance data

Unusual Attitude Recovery		
	HUD	HDD
Reaction Time (s)		
Nose-Up	1.498	1.514
Nose-Down	1.466	1.433
Response Accuracy		
Nose-Up	95.9%	97.5%
Nose-Down	97.8%	98.5%
Precision Instrument Control		
	HUD	HDD
RMS Alt Dev (ft)	27.655	59.146*
RMS A/S Dev (kts)	3.348	5.186*
RMS Gamma Dev (deg)	0.485	1.108*
RMS Bank Dev (deg)	2.800	2.602
RMS Heading Dev (deg)	1.016	1.514*
ILS Approach		
	HUD	HDD
RMS Heading Dev (deg)	1.314	1.848
RMS Alt Dev (ft)	38.394	75.044*
RMS A/S Dev (kts)	20	6.492*
RMS GS Dev (deg)	0.246	0.382*
RMS Local Dev (deg)	0.095	0.141*

* - significant at the $p<0.05$ level

Pilot Questionnaires

In general, pilot response to the HUD symbology was positive. Figures 6 and 7 indicate that for both head-up and head-down presentations, the pilots were able to effectively interpret attitude information. These responses further indicate that although pilots were confident of their attitude using the HUD, they expressed a higher degree of comfort

with the head-down instrumentation. Several pilots commented that this trend is most likely due to the greater exposure that pilots have had to the head-down instrumentation and felt that the comparable comfort level could be achieved given extended use of the HUD.

With regard to the ILS and PICT tasks, pilots were unanimous in their preference for the HUD. A complete review of the pilot responses to the debrief questionnaires is provided in Appendix C.

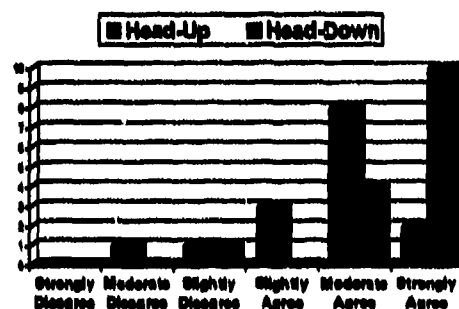


Figure 6. Pilot Responses to the statement "I was able to rapidly determine what unusual attitude I was in as soon as I saw the display"

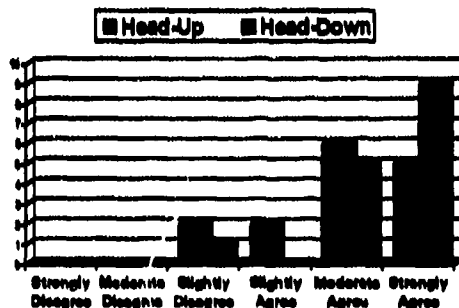


Figure 7. Pilot Responses to the statement "At first glance at the display I was able to determine which control inputs were required for recovery"

PHASE I CONCLUSION

The results of the Phase I evaluation suggested that during precision instrument control and precision ILS approach tasks, pilots performed significantly better when flying with the HUD as their primary flight reference, as opposed to the standard F-16 electro-mechanical instrumentation. For the unusual attitude recovery task, however, the results suggested that pilots' reaction times were not significantly different between head-up and head-down instrumentation. A review of the debrief comments suggested that pilots were comfortable

with the notion of using this HUD symbology and mechanization as a primary flight reference.

PHASE II

Based on the outcome of the simulator evaluation the decision was made to initiate the flight test portion of the validation process. As a result of this flight test program, several issues regarding symbology format, symbology mechanization and evaluation procedures were identified. Issues identified by the flight test program were as follows:

Caging Mechanization. During the Phase I simulation program, the Climb/dive marker (CDM) was mechanized such that the symbol was restricted to the centerline of the Total Field-of-View (TFOV) of the HUD. However, in order to maintain horizon correlation at high bank and drift angles, the mechanization also allowed for the drifting of the CDM from the HUD centerline. The flight test pilots reported that under high bank angle/high crosswind conditions, the CDM was permitted to drift toward the outer edges of the Instantaneous Field-of-View (IFOV). Pilot comments during the flight test program indicated that this particular mechanization inhibited their ability to rapidly determine their attitude and thus affecting recovery performance.

As a result, a modification to the caging mechanization was implemented for Phase II. The new mechanization ensured strict caging of the CDM to the HUD centerline but at the expense of horizon correlation at high bank/beta angles. The equations used to determine positioning of the CDM relative to the FPM can be found in Appendix A.

Pitch Transition. During Phase I simulation, the CDM, whenever limited at the IFOV, would transition the climb/dive ladder, over a period of 2 seconds, from the CDM to the waterline reference. During flight testing, pilots reported that in many cases the climb/dive ladder was in the course of transition from the CDM to the waterline reference upon initiation of the unusual attitude recovery. As a result, the pilots were provided with no reference to the attitude scale, creating confusion which may have adversely affected the pilots ability to interpret the display.

The Phase II mechanization provided that in the event the CDM became limited by the IFOV, the ladder would remain referenced to the climb/dive marker. Such a mechanization provided the pilot with a consistent control reference which continually presented accurate climb/dive angle information.

The down side to this approach was the loss of correlation between the climb/dive ladder and the outside world when the CDM became limited. This type of mechanization created some concern in low speed situations. One of the cues that pilots often use to determine that the aircraft is approaching a stall condition in existing HUDs is the depression of the CDM as the angle-of-attack increases.

The modified mechanization did not provide this form of cueing. To compensate for this deficiency, the mechanization was supplemented such that when the CDM became limited at the IFOV, the CDM was replaced with a dashed or "ghosted" CDM and an analog Vertical Velocity Indicator (VVI) was displayed about the altitude scale (See Appendix A). The dashing of the CDM cued the pilot to the high AOA condition while the VVI provided sink rate information.

Climb/Dive Ladder. The fundamental concept behind the design of the climb/dive ladder adopted in the provisional HUD was to incorporate as much asymmetry as possible between positive and negative climb/dive angles. A significant element of this asymmetry was the incorporation of articulated ladder lines to represent climb angles, and tapering lines to represent dive angles. The original design called for the articulated lines to represent negative dive angles. However, there was some concern that the presence of articulated lines would inhibit accurate interpretation of roll angle and potentially increase error rates for unusual attitude recoveries. A study conducted to determine the effect of articulation on recovery accuracies seemed to confirm this concern (Weinstein and Ercoline, 1990). Because the nose-down recoveries were deemed more critical, the technical team decided that if the articulation was a potential source of confusion, the presentation of ladder articulation should only occur for positive climb/dive angles.

However, during flight test, pilots reported difficulty in recognizing their attitude during several of the steep nose-down recoveries. In fact, further analysis of the Phase I simulation data appears to confirm this finding. A post-hoc analysis of the

Phase I simulator data for the -60° unusual attitude recoveries indicated a significant difference between head-up and head-down displays; $F(1,22)=10.59$, $p<0.0036$. Mean reaction time for the HUD was 1.493s versus 1.411s for the head-down instruments with essentially equivalent accuracy rates suggesting that pilots actually performed better when presented with the articulated climb/dive ladder lines.

Due to these conflicting data, a follow-up study was conducted to determine the appropriate configuration for the climb/dive ladder; articulated lines above the horizon or below the horizon (Hughes and Hassoun, 1992). Results of the study indicated that pilots actually performed better when provided with articulated lines whether nose-up or nose-down. A decision was then made, based on the criticality of severe nose-low attitudes, to adopt a configuration which presented the articulated lines for negative climb/dive angles and straight-tapered lines for positive climb/dive angles.

AOA Error and Energy Management Cueing. Recently, researchers at Brooks AFB conducted an evaluation comparing several AOA Error cueing symbology with the incorporation of energy management cueing (Weinstein and Ercoline, 1992). Results of the study indicated that an alternative to the AOA bracket currently used in the F-16 and F-15 actually resulted in superior pilot performance. Therefore, the AOA Error Worm (see Appendix A) was incorporated into the provisional standard for the Phase II evaluation. Results also indicated that airspeed control was further enhanced by the incorporation of a longitudinal acceleration or energy management cue. The cue was to be used in conjunction with the AOA Error cue to correct airspeed to maintain appropriate AOA.

Climb/dive marker and Flight Path Marker. The final significant change to the provisional standard was the modification to the CDM and the FPM. There was concern that adopting the symbol geometry of what has previously represented flight path as the climb/dive marker could generate confusion for the pilots. For this reason, a new symbol was created to represent climb/dive angle (see Appendix A) and the original geometry of the FPM was maintained. However, to eliminate the potential for distraction and confusion, the FPM symbol was reduced to 30% of its original size. The reduction was necessary because the conflict between the two symbols (i.e., CDM and FPM) has been shown to create confusion and serve as a distraction

to pilots. The reduced FPM provided the pilots with a salient representation of flight path while not creating a distraction which might draw attention away from the CDM.

PHASE II METHOD

Apparatus

Refer to Phase I of this report for a description of the apparatus used during the Phase II evaluation.

Baseline Head-Up Display. The baseline HUD symbology used during Phase II in Figure 8. A detailed description of the geometry and functionality of symbology included in the provisional HUD symbology standard is provided in Appendix A.

Subjects

A total of 15 volunteer pilots participated as subjects in the simulator validation effort. Pilots participating in this study included three test pilots from the Air Force Flight Test Center, one IFC pilot and 11 TAF pilots. All of the pilots had at least some experience with instrument flying using HUD symbology. A review of pilot experience levels is provided in Table 6.

Table 6. Subject pilot experience

Aircraft	No. of pilots	Avg HUD Experience (hrs)
F-16	7	640
A-10	3	950
F-15	4	940
A-7	1	800
Totals	15	790

Procedure

Instrument Flying Tasks. The three tasks (1) unusual attitude recovery, (2) precision approach, and (3) precision instrument maneuvering developed during the Phase I simulation were modified for Phase II based on lessons learned during the Phase I flight test program. These modifications are as follows:

Unusual Attitude Recovery. The same unusual attitude recovery procedure was used in Phase II as in Phase I with two exceptions. Lessons learned from the flight test program stressed the importance of dynamic entry into the unusual attitude. Phase I trials were initiated with the aircraft in a static position at 0° AOA and therefore any effects due to aircraft dynamics would not have been demonstrated. As a result, all Phase II trials were initiated by having a robot pilot fly the simulator into the desired configuration at which time the start tone was presented, instructing the pilot to open his eyes and recover the aircraft.

The second modification was the incorporation of winds during the recoveries. Flight test pilots reported that the lateral movement of the CDM during the Phase I flight test was significantly aggravated by the presence of gusting crosswind. To ensure that such effects were demonstrated in Phase II simulation, variably gusting winds from 30 to 45 kts were incorporated into the simulation. The implementation of the robot pilot coupled with the incorporation of the crosswind model more closely approximated conditions experienced during flight testing.

Precision Instrument Control Task. Pilots during Phase II were instructed to fly the PICT in the same fashion as during Phase I. The only difference between the procedure used during Phase I and Phase II was the incorporation of a East/West version of the profile used in Phase I in which each of the heading flown were 180° out of phase. Trials were randomly assigned to one of the two profiles.

Precision Approach. The procedures for Phase II were identical to those implemented during Phase I.

The focus of the validation effort was placed primarily on the use of the HUD as a primary flight reference during instrument flying tasks. However, if adopted as a standard, it is paramount that the symbology also be compatible with the requirements of other mission tasks (i.e., low-level navigation, air-to-ground/air-to-air engagements etc.). Therefore, the combined use of the standard symbology with other mission essential symbology was to be demonstrated as part of the overall validation effort. The air-to-ground weapons delivery task described below was developed for the sole means of identifying potential incompatibilities between the baseline symbology and existing air-to-ground mission symbology.

Air-to-Ground Weapons Delivery. An air-to-ground mission profile was developed in which pilots were required to navigate at low level to a target area, perform a pop-up maneuver, and deliver a weapon to a predefined target location. The profile consisted of three targets and five waypoints.

Pilots were instructed to navigate from waypoint to waypoint while maintaining 300 ft AGL and approximately 480 kts. When approaching the target area the profile called for an action-off to the right 30°, a 30° climb to 4000 ft and a left roll-in to the target area. Upon acquiring the target, pilots were instructed to switch to the air-to-ground mode for weapons delivery. After release, pilots egressed to the left, switched back to NAV mode and proceeded to the next waypoint. Upon egress from the final target area, the simulator was reset to the initial conditions for the next mission. Winds varied from 10 to 20 kts coming from either the north or south to achieve maximum drift effects.

In performing the mission, the baseline HUD was supplemented with three additional symbols: steer point index, point-of-interest box, and Continuously Computed Impact Point (CCIP) with bombfall line. (Note: These symbols do not represent an attempt to standardize mission symbology but were used merely for demonstration.) The symbols used during the air-to-ground missions are presented in Figures 9 and 10.

The steerpoint index symbol provided the pilot with command steering from waypoint to waypoint. The symbol was mechanized such that it provided steer cueing relative to the CDM. By banking the aircraft until the cue centered on the CDM, the pilot navigated from point to point. When the cue centered on the CDM during level flight the aircraft was on a direct course to the next waypoint/target.

The point-of-interest box designated the position of the current point-of-interest (i.e., waypoint or target). The box was positioned on the HUD such that would overlay the location of the point-of-interest on the visual scene. During the weapon delivery, it was used in similar fashion as a target designator, cueing the pilot to the target location.

The CCIP was used to represent the weapon impact point given an instantaneous weapon release.

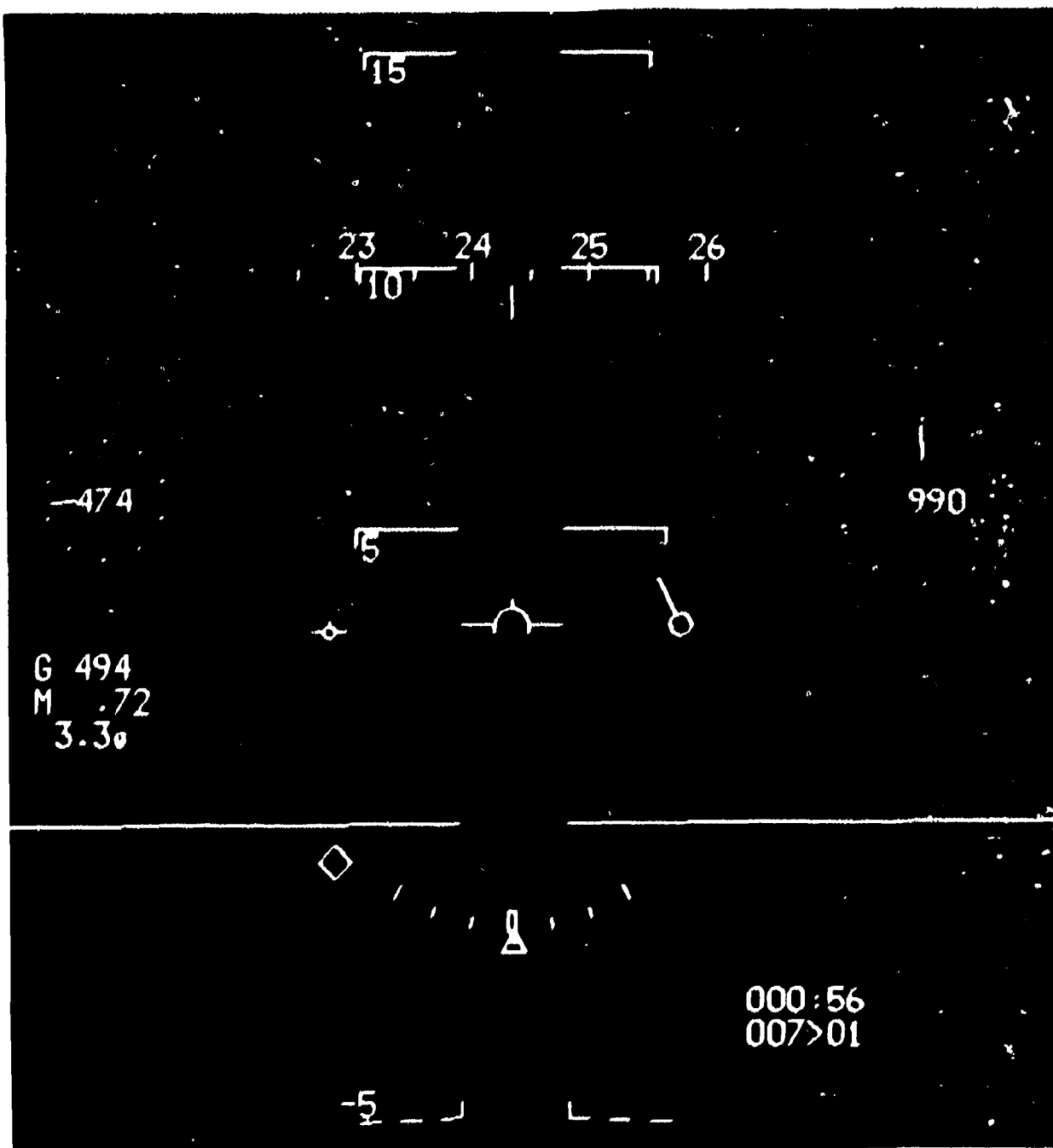


Figure 9. Mission Modified Symbolology (Steerpoint Index)

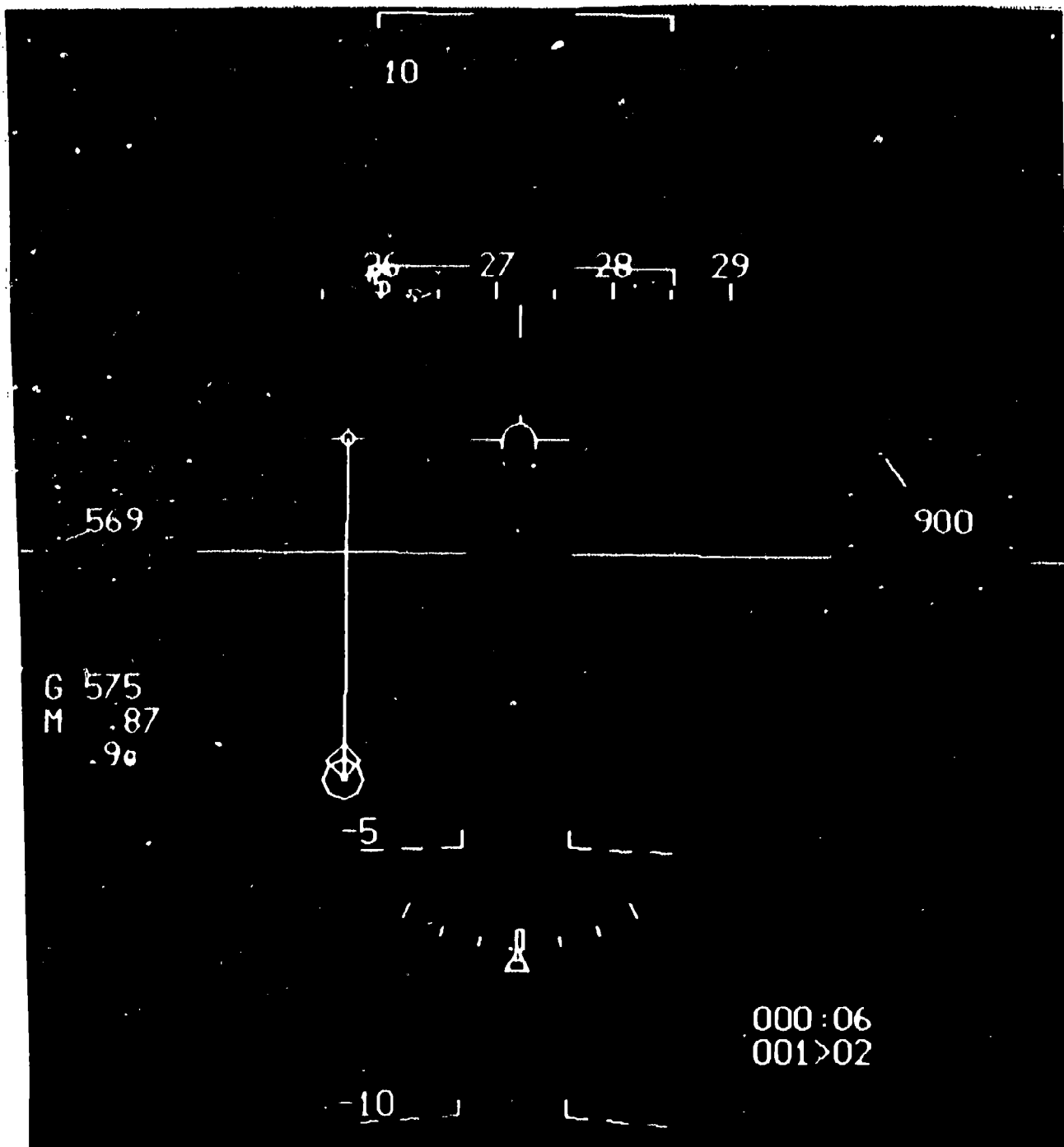


Figure 10. Mission Modified Symbolology (CCIP and Bombfall Line)

The CCIP was connected to the FPM by the bombfall line. The pilots used the CCIP and bombfall line by controlling aircraft flight path such that the FPM was positioned just fore of the target area allowing the bombfall line to bisect the target area. As the aircraft ingressed to the target the CCIP began approaching the target area. When the CCIP overlaid the target area, the pilot depressed the weapon release switch releasing the weapon. The algorithm used to calculate impact point was based on current F-16 Block 30 mechanization.

Pilot Training. For the three instrument tasks for which data were to be collected, training was conducted in similar fashion as during Phase I. Because the air-to-ground mission was being flown for demonstration purposes only, no formal training was provided; however, pilots were encouraged to fly as many missions as simulator time allowed. All pilots flew a minimum of six missions prior to completing the debrief questionnaire.

Data Collection

The performance measurands collected during Phase II were the same as those collected during Phase I. Refer to Phase I Data Collection for a review of variables collected during each task.

SWORD. In addition to the data collected during Phase I, Phase II also incorporated the Subjective Workload Dominance (SWORD) technique (Vadulich, 1989). SWORD uses a series of relative judgments comparing the relative workload of different task and display conditions. These relative judgments are used to generate a mean rating for each task/display configuration which are in turn statistically compared. The SWORD analysis was conducted using a 2x3 repeated measures ANOVA comparing display type (HDD vs. HUD) and instrument flying task (UAR vs. ILS vs. PICT). A copy of the SWORD data collection sheets are provided in Appendix D.

Pilot Questionnaires. At the conclusion of data collection each subject pilot was asked to complete a debrief questionnaire. A copy of the questionnaire given to the pilots is provided in Appendix E.

PHASE II RESULTS

A review of the performance data means for each of the flying tasks performed during the

evaluation is provided in Table 7. A $p < 0.05$ level was used as a criterion for rejecting the null hypothesis.

Unusual Attitude Recovery

Data collected during the unusual attitude recovery task included reaction time to first correct control input and accuracy of initial control input. Pilots' reaction time and accuracy rate data were analyzed as a comparison of HUD and HDD using four one-way ANOVAs for each flight path angle condition (60° , 30° , -30° , and -60°). The ANOVAs indicated no significant main effects for display type. However, there appears to be a definite trend toward higher response accuracy while using the HUD for the -60° condition, $F(1,14)=3.59$, $p < 0.0790$, and the -30° condition, $F(1,14)=4.17$, $p < 0.0604$.

Precision Instrument Control

A one-way repeated measures analysis of variance was conducted on the data to identify pilot performance differences between the two display conditions, HUD and HDD, during the Precision Instrument Control task. As in Phase I results indicated a statistically significant performance enhancement when using the HUD for RMS Altitude Deviation, $F(1,14)=61.23$, $p < 0.0001$; RMS Airspeed Deviation, $F(1,14)=30.15$, $p < 0.0001$; RMS Flight Path Angle, $F(1,14)=106.39$, $p < 0.0001$; RMS Heading Deviation, $F(1,14)=5.71$, $p < 0.0316$.

ILS Approach

A one-way repeated measures ANOVA was conducted on the data to identify pilot performance differences between the two display conditions, HUD and HDD, during the ILS Approach task. Analyses indicated a statistically significant performance enhancement when using the HUD over the HDD for RMS Altitude Deviation, $F(1,14)=33.80$, $p < 0.0001$, RMS Airspeed Deviation, $F(1,14)=14.85$, $p < 0.0018$, RMS Localizer Deviation, $F(1,14)=32.48$, $p < 0.0001$.

SWORD

A 2x3 ANOVA of the SWORD data indicated a significant interaction between display type (HUD vs. HDD) and task (Unusual Attitude Recovery vs. ILS Approach vs. Precision Instrument

Control), $F(2,22)=22.44$, $p<0.0001$. An analysis of the simple main effects by task indicated a significant reduction in workload for the HUD during the ILS Approach, $F(1,11)=54.82$, $p<0.0001$; and Precision Instrument Control, $F(1,11)=14.99$, $p<0.0026$. However, the reverse was true for the Unusual Attitude Recovery, showing a statistically significant reduction in workload for the HDD during unusual attitude recoveries, $F(1,11)=4.88$, $p<0.0494$. Means for the SWORD ratings are presented graphically in Figure 11.

Table 7. Performance data means

Unusual Attitude Recovery

	HUD	HDD
Reaction Time (s)		
60° Gamma	1.399	1.403
30° Gamma	1.346	1.330
-30° Gamma	1.224	1.320
-60° Gamma	1.269	1.306

Response Accuracy

60° Gamma	94.5%	94.2%
30° Gamma	96.3%	98.7%
-30° Gamma	98.2%	94.9%
-60° Gamma	98.7%	95.7%

Precision Instrument Control

	HUD	HDD
RMS Alt Dev (ft)	16.950	37.561*
RMS A/S Dev (kts)	2.892	4.563*
RMS Gamma Dev (deg)	0.602	1.267*
RMS Bank Dev (deg)	1.993	1.937
RMS Heading Dev (deg)	0.718	1.830

Precision Approach

	HUD	HDD
RMS Heading Dev (deg)	1.424	1.760
RMS Alt Dev (ft)	23.478	61.640*
RMS A/S Dev (kts)	5.273	7.731*
RMS GS Dev (deg)	0.228	0.765
RMS Local Dev (deg)	0.088	0.179*

* - significant at the $p<.05$ level

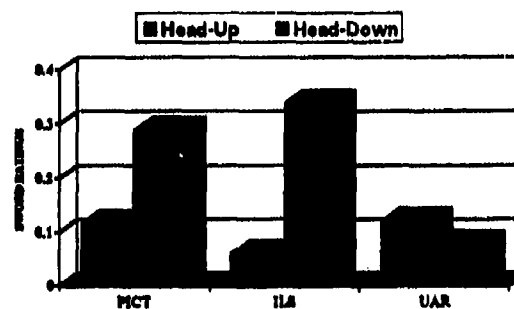


Figure 11. SWORD Data

Questionnaires

As in Phase I, pilot response to the HUD symbology was positive. Figures 12 and 13 indicate the pilots' perceived ability to interpret attitude information presented in the HUD versus head-down. These responses indicate that although pilots were confident of their attitude using the HUD, they expressed a higher degree of comfort with the head-down instrumentation. This conclusion is reflected in the increased number of strongly agree ratings given for the head-down instruments. Several pilots commented that this trend is most likely due to the greater exposure pilots have had to the head-down instrumentation, and felt that a comparable comfort level could be achieved with the HUD given extended use.

With regard to the ILS and PICT tasks, pilots unanimously preferred the HUD over the HDD (Figures 14 and 15). However, one of the greatest complaints regarding the HUD during the ILS Approach was the clutter generated by the sheer amount of symbology presented.

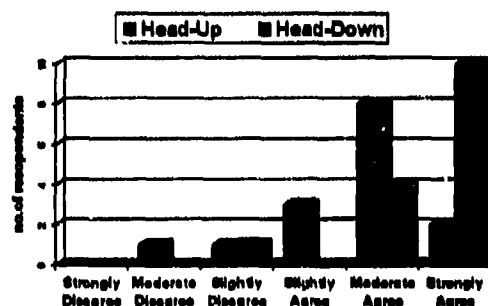


Figure 12. Pilot Responses to the statement "I was able to rapidly determine what unusual attitude I was in as soon as I saw the display"

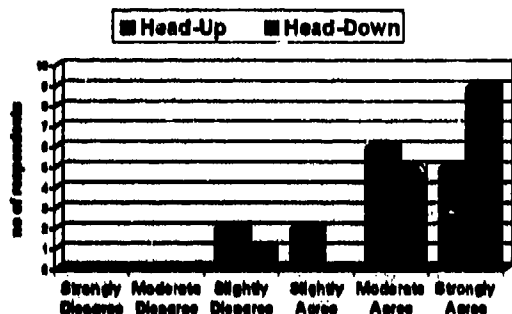


Figure 13. Pilot Responses to the statement "At first glance at the display I was able to determine which control inputs were required for recovery"

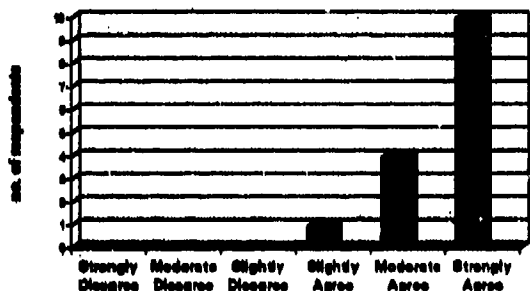


Figure 14. Pilot Responses to the statement "The HUD was easier than the HDD when performing the ILS task."

When asked whether they would feel comfortable using the HUD symbology as their primary flight reference a strong majority of the pilots responded in the affirmative (Figure 16). Two pilots disagreeing stated that they felt that a requirement for head-down instrumentation was still valid and that the quality of attitude information presented via an ADI (i.e., contrast between nose-up and nose-down attitudes) could not be replicated in a HUD format.

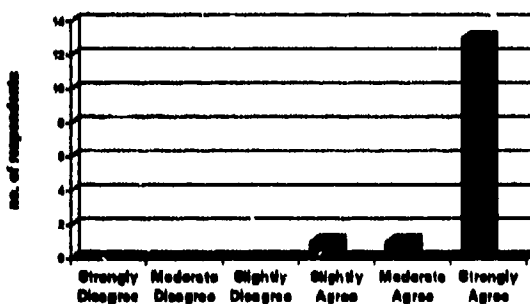


Figure 15. Pilot Responses to the statement "The HUD was easier than the HDD when performing the PICT task."

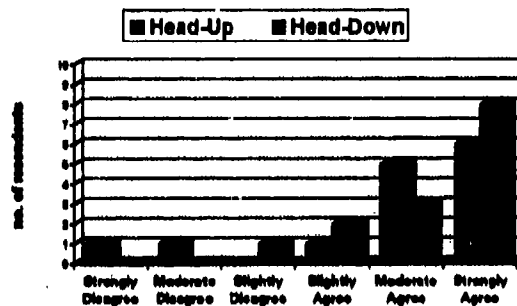


Figure 16. Pilot Responses to the statement "I would feel comfortable using the display as my primary flight reference for both instrument flying and unusual attitude recoveries."

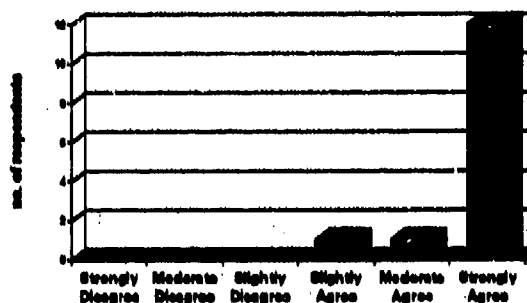


Figure 17. Pilot Responses to the statement "Given sufficient training with the present symbology I feel I could successfully accomplish the bombing mission."

When asked whether they could accomplish the air-to-ground mission using the provisional symbology, the pilots unanimously responded in the affirmative (Figure 17). Several pilots commented that the separation of the CDM and FPM provided additional information regarding magnitude of drift and correction factors which their present HUDs did not provide.

A complete review of the pilot responses to the debrief questionnaires is provided in Appendix F.

DISCUSSION

The present evaluation was conducted as part of a validation effort to certify the provisional HUD symbology suite as a primary flight reference. This was accomplished by comparing pilot performance data with the HUD symbology versus a modified F-16 head-down instrument display suite while flying three flight tasks, 1) unusual attitude recovery, 2) precision instrument control, and 3) ILS approach. The remainder of the report will discuss

the results of these comparisons and review pilot subjective reaction to the adoption of the HUD as a primary flight reference, as well as criticisms and potential improvements to both the symbology set and the methodology used to validate it.

ILS Approach and Precision Instrument Control Task

The results of the evaluation suggested that pilots performed better using the HUD symbology for tasks requiring precise flight control (i.e., ILS Approach and PICT). One obvious explanation for such results can be found in the relative sizes, in terms of visual angle, the two displays subtend. Because the HUD is conformal with the real world, at least at low climb/dive angles, a five degree change in flight path is represented on the HUD by a five degree visual angle change in the position of the CDM relative to the climb/dive ladder. The attitude scale provided by the F-16 attitude indicator represents the same five degree change in flight path with a one degree visual angle change in the relative position of the attitude scale and its reference. What this means in practical terms is that the conformal display provides a much higher degree of resolution to the pilots for precise control of flight path during precision instrument maneuvering. It is this difference which is most likely responsible for the improved performance while flying with the HUD during the precision flying tasks.

A second explanation for the difference in performance stems from the type of information each of the displays provides. The HUD provides flight path angle as its control reference; whereas the ADI presents pitch attitude as its control reference. During precision flight control, pilots were particularly interested in where their aircraft was going as opposed to where the nose was pointed. In order to determine flight path angle when flying with an ADI, the pilot must integrate pitch attitude with angle-of-attack, vertical velocity and airspeed. The presentation of flight path angle in the HUD eliminates the need for the pilot to mentally calculate flight path angle.

It is not surprising therefore that pilots expressed an overwhelming preference for the HUD during the ILS approach and precision instrument control tasks. Several pilots justified their responses, citing one or both of the previous explanations, while

others merely indicated that the HUD was simply more intuitive than the ADI.

A recurring criticism of the symbology suite was the absence of a Vertical Velocity Indicator (VVI) during the ILS Approach task. During the development of the provisional symbology set, it was regarded that the CDM and VVI essentially presented the same information, rate of descent. The elimination of the VVI was a means of reducing display clutter as well as demands for write-time on the display unit. The concern expressed by several of the pilots indicates that VVI presentation be remechanized such that presentation of vertical velocity be pilot selectable.

A second recurring criticism recorded was the degree to which the symbology cluttered the display. Several pilots complained that the symbology clutter could potentially obstruct their view of the runway during the visual portion of the approach. A number of pilots commented that the information as presented was very effective during the instrument portion of the approach; however, once they had transitioned to a visual approach, the clutter of the display became a potential problem. One recommendation was to provide a declutter option which would enable the pilot to remove unnecessary information during certain portions of the approach.

Because of the recurring nature of the clutter issue, it is reasonable to conclude that if improvements are to be made to the current symbology, the reduction of the symbology clutter should be a major focus.

In criticizing the methodology adopted in validating the symbology, the pilots commented that the F-16 instruments are extremely small and therefore require greater effort to interpret. However, the selection of the F-16 as the baseline was justified by the stipulation that the HUD must perform as good or better than existing head-down instrumentation. The F-16 represents the most prolific airframe in the Air Force inventory today. Therefore, if any standard for head-down instrumentation does exist, it is reasonable to assume that the performance of the F-16 represents that standard.

Unusual Attitude Recovery

One feature of the symbology evaluated in Phase I which may explain the difficulty pilots experienced during nose-low recoveries was the configuration of the climb/dive ladder. The climb/dive ladder was configured such that the ladder lines got smaller as the rate of descent it referenced increased (i.e., tapering). At large dive angles, these ladder lines became so small (30% of 5° ladder lines) the lack of cueing could have inhibited the pilots ability to determine pitch and roll attitudes.

During the Phase II simulation the change made to the climb/dive ladder, by placing the articulated ladders lines below the horizon, seemed to dramatically improve both recovery performance and the pilot acceptance of the symbology for the nose-low conditions. However, pilots did comment that they were less confident of their attitude for the nose-high conditions. This decrease in confidence in attitude awareness seems to be reinforced by the decrease in performance for both reaction time and response accuracy for the nose-high conditions. Such would suggest that the effect of tapering, although incorporated to enhance attitude awareness, may actually have the opposite effect and should be re-examined in follow-on evaluations.

A review of the subjective questionnaire responses (Appendix F) would suggest that pilots felt comfortable with the provisional HUD symbology set as a primary flight reference. Most were also in agreement that the HUD would be a safe instrument for recognition of and recovery from unusual attitudes. However, several pilots commented that although they felt comfortable with the HUD, they were not prepared to abandon the use of traditional head-down instrumentation and would suggest that presentation of attitude information head-down continue in future aircraft.

Much of the reluctance seems to be based on what many considered inherent weaknesses with HUDs as primary flight displays. The HUD, by definition, is an eyes-out-of-cockpit display and as a result makes the pilot susceptible to many of the illusory effects of cultural or meteorological conditions. For this reason alone, it may be necessary to maintain the capability to present head-down attitude information in some form which

enables the pilot to both recognize and recover from unusual attitudes.

Air-to-Ground Weapons Delivery

During the air-to-ground weapons delivery mission, pilots reported no difficulty using the provisional symbology in such a weapon delivery role. The original concern using the provisional symbology was the ability of the pilots to coordinate the use of the CDM for course steering and navigation and the FPM for ground clearance cueing and weapon delivery. Of all pilots participating, none expressed any difficulty in integrating the two symbols while executing the mission. Several pilots commented that the separation of the CDM and FPM actually increased situational awareness by establishing a stable control reference for navigation while providing a indication of the direction and magnitude of any wind effects.

CONCLUSION

The results of this evaluation suggested that during precision instrument control and precision ILS approach tasks, pilots performed significantly better when flying with the HUD as their primary flight reference, as opposed to the standard F-16 electro-mechanical instrumentation. For the unusual attitude recovery task however, the results suggested that pilots' reaction times were not significantly different between head-up and head-down instrumentation. Analysis of error rates did indicate a trend toward higher accuracy while recovering using the head-up display symbology.

Subjectively, pilots during both phases of the simulator validation program seemed confident that the HUD symbology test was adequate as a primary flight reference. Several pilots felt that although the HUD could be used as a primary flight reference, there remains a requirement for head-down instrumentation to include a centrally located attitude indicator.

REFERENCES

Air Force Manual 51-37, (1986). Flying Training -- Instrument Flying. Headquarters US Air Force, Washington DC.

US Department of the Air Force, Office of the Chief of Staff, (1989). Air Force Instrument Standardization Working Paper.

Evans, R., Bitton, F., (1990). Report on Head-Up Display Symbology Standardization. Technical Report, USAF Instrument Flight Center, Randolph AFB, Texas.

Hall J.R., Pinwell, J.C., (1989). RAE Fast-Jet Format - Specification Issue 2. Working Paper 89/034. Royal Aerospace Establishment, Bedford, UK.

Hughes, T.C., Hassoun, J.A., (In draft). A Review of Alternative HUD Symbology Formats for Fighter Attack Aircraft. Technical Report, Aeronautical Systems Center, Wright-Patterson AFB, Ohio.

Hughes, T.C., Hassoun, J.A., (1990). A Comparison of Alternative Head-Up Display Symbol Sets during Approach and Landing, Navigation, and Unusual Attitude Recovery Tasks. Technical Report, Crew Station Evaluation Facility, Wright-Patterson AFB, Ohio

Vadulich, M., (1989). The use of judgment matrices in subjective workload assessment: The Subjective Workload Dominance (SWORD) technique. In the proceedings of Human Factors Society 33rd Annual Meeting, Vol. 2, (pp. 1406-1410). Santa Monica, CA: Human Factors Society.

Ward, G.F. and Hassoun, J.A., (1990). The Effects of Head-Up Display (HUD) Pitch Ladder Articulation, Pitch Number Location and Horizon Line Length on Unusual Attitude Recoveries for the F-16. Technical Report, Aeronautical Systems Division, Wright-Patterson AFB, Ohio.

Weinstein, L and Ercoline, W , (1991). Effects of variations in head-up display climb/dive ladder symbology. In: Proceedings of the Human Factors Society 35th Annual Meeting, Santa Monica, CA.

Weinstein, L and Ercoline, W (1992). An evaluation of Alternative Energy Management Cueing symbology. (Manuscript to be published)

APPENDIX A

MECHANIZATION OF THE INSTRUMENT FLIGHT STANDARDIZATION HEAD-UP DISPLAY (HUD) SYMBOLOGY

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October 1992

DRAFT REPORT FOR 08/01/91 - 07/01/92

**DCS FOR INTEGRATED ENGINEERING AND TECHNICAL MANAGEMENT
AERONAUTICAL SYSTEM CENTER
AIR FORCE MATERIAL COMMAND
WRIGHT-PATTERSON AFB OH**

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1. INTRODUCTION

1.1. SCOPE OF DOCUMENT

This document describes the Instrument Flight Symbolology (IFS) Head-Up Display (HUD) symbology as it is implemented at the Crew Station Evaluation Facility (CSEF) at Wright Patterson AFB, Dayton, Ohio. The document consists of five sections and two appendices.

Section 1, Introduction, defines the scope of the document, states the assumptions used in implementing the HUD symbology at the CSEF, summarizes HUD symbology, and defines the fields of view, reference points, and acronyms.

Section 2, Aircraft Reference Symbolology, describes symbols that are positioned against the aircraft reference point excluding the navigational symbology.

Section 3, HUD Scales, describes the speed, altitude, radar altitude, heading, and roll scales.

Section 4, Navigational Symbolology, describes the navigational symbology.

Section 5, Text Readouts, describes the two groups of text readouts located on the lower left and right sides of the HUD.

Section 6, Positioning and Quickening, explains the algorithms used to "quicken" and position the climb-dive marker, flight path marker, and the climb-dive ladder.

Section 7, Compression, explains the algorithms used to compress the climb-dive ladder.

1.2. DEFINITION OF TERMS

The HUD was implemented at the CSEF using an F-16 C/D Block 25 HUD. The HUD fields of view and reference points are defined based on the physical limitations of this HUD. Details of the F-16 HUD can be found in GEC Avionics document number 29/2783/1/T10, "Computer Program Development Specification For The F-16 Head Up Display Operational Flight Program", October 1988.

1.2.1. Measurement System

To ensure that all symbol dimensions remain constant for any physical display size or location, all HUD

measurements are given as units of milliradians of visual arc. A milliradian is 0.001 radians or 0.057 degrees.

1.2.2. Fields of View

A field of view is defined as "the area visible through the lens of an optical instrument."¹ There are two fields of view associated with the HUD; the total field of view and the instantaneous field of view.

Total Field Of View (TFOV) is the total graphical display area visible through the HUD. The TFOV is limited by the HUD's graphical display system (e.g., CRT size) and its optical system.

Instantaneous Field Of View (IFOV) is the portion of the HUD's TFOV that the pilot can see when his head is at the design eye point. The pilot must move his head to see the remaining portions of the TFOV that are outside the limits of the IFOV.

1.2.3. Reference Points

All the HUD's symbology is referenced against either one of four fixed reference points or other HUD symbology. The four fixed reference points are the center total field of view, the aircraft reference point, the left hand reference point, and the right hand reference point.

Center Total Field of View (CTFOV) is the center of the TFOV.

Aircraft Reference Point (ARP) is defined as the point on the HUD that a line, which extends from the design eye point and is parallel to the aircraft reference line, passes through. The Climb-Dive Marker and Flight Path Marker are referenced from this point. In the CSEF HUD, the ARP is located 6 degrees above the CTFOV.

Left Hand Reference Point (LHRP) is a movable point against which the speed scale is positioned. The LHRP is lowered during ILS mode or with landing gear down. In the CSEF HUD, the LHRP is located 122 mr left and 58 mr above the CTFOV. During ILS mode or when landing gear is down, the LHRP is lowered 68 mr to a position of 122 mr left and 10 mr below the CTFOV.

¹ Webster's New Collegiate Dictionary, G. & C. Merriam Co., 1981

Right Hand Reference Point (RHRP) is a movable point against which the altitude scale is positioned. The RHRP is lowered during ILS mode or with landing gear down. In the CSEF HUD, the RHRP is located 122 mr right and 58 mr above the CTFOV. During ILS mode or when landing gear is down, the RHRP is lowered 68 mr to a position of 122 mr right and 10 mr below the CTFOV.

The LHRP and RHRP always have the same vertical position and are of equal horizontal distance from a vertical line running through the CTFOV. The vertical positions are chosen to keep the Climb-Dive Angle Marker between the speed and altitude scales during normal cruise flight and ILS modes. The horizontal distance is chosen to put the scales near the inside edge of the IFOV.

1.3. HUD OVERVIEW

An example of the IFS HUD is shown in Figure 1-1. The symbology has been categorized as follows:

1. Aircraft Reference Symbology
2. Scales
3. Navigational Symbology
4. Text Readouts

Insert Figure 1-1. -- Example Of The IFS HUD
(Need a postscript image of the HUD from the scanner)

1.3.1. Aircraft Reference Symbology

The aircraft reference symbology includes the Climb-Dive Angle Marker (CDM), Flight Path Marker (FPM), Climb-Dive Ladder (CDL), Longitudinal Acceleration Cue (LAC), and Speed Worm (SW).

1.3.2. Scales

Scales are used to display the aircraft's speed, barometric altitude, radar altitude, heading, and roll. All scales, except the roll scale, are positioned against the left and right hand reference points (LHRP and RHRP). The roll scale is centered about the Center of the Total Field Of View (CTFOV).

1.3.3. Navigational Symbology

The navigational symbology provides the pilot with information about his location and steering commands to return to a designed flight path or course. The symbology consists of a Course Deviation Indicator

(CDI), a Vertical Deviation Indicator (VDI), Flight Director Steering Bars, and a TACAN Indicator. The CDI, VDI, and steering bars are located relative to the CDM. The TACAN indicator is positioned relative to the CTFOV.

1.3.4. Text Readouts

The HUD has two groups of text readouts; one on each side of the HUD. The left side includes CDI sensor and course readouts. The right side includes TACAN DME, TACAN channel number, and time readouts. The readouts are located inside the lower left and right corners of the IFOV and do not move with the left and right hand reference points.

1.3.5. HUD Modes

Many of the HUD symbols are only displayed in certain modes. Currently, the following three navigational modes have been defined:

Up and away	- Normal takeoff and flight mode
TACAN - Tacan Navigation mode	
ILS	- ILS mode

1.3.6. HUD Character Set

The CSEF HUD uses the F-16's character set. The full size characters are 7 mr high by 4 mr wide. This character set is shown in Figure 1-2.

ABCDEFGHIJKLM
 NOPQRSTUVWXYZ
 0123456789
 *, ° = ⊕ < - + > ; / '

Insert Figure 1-2. -- HUD Character Set

1.4. ACRONYMS

AOA	Angle Of Attack
ARP	Aircraft Reference Point
CDM	Climb-Dive Angle Marker
CDI	Course Deviation Indicator
CDL	Climb-Dive Ladder
CSEF	Crew Station Evaluation Facility
CTFOV	Center Total Field of View
DCDM	Dashed Climb-Dive Angle Marker
DME	Distance Measurement Equipment
FOV	Field of View
FPM	Flight Path Marker
GHL	Ghost Horizon Line
HL	Horizon Line
HUD	Head Up Display
IFOV	Instantaneous Field Of View
IFS	Instrument Flight Symbolology
ILS	Instrument Landing System
LAC	Longitudinal Acceleration Cue
LHRP	Left Hand Reference Point
MDA	Minimum Descent Altitude
mr	Milliradian
RHRP	Right Hand Reference Point
SW	Speed Worm
TFOV	Total Field of View
VDI	Vertical Deviation Indicator
VVI	Vertical Velocity Indicator

2. AIRCRAFT REFERENCE **SYMBOLGY**

Aircraft reference symbolgy include a Flight Path Marker, Climb-Dive Angle Marker, Climb-Dive Ladder, Longitudinal Acceleration Cue, and a Speed Worm. These symbols display the aircraft's flight path, climb-dive angle, roll angle, longitudinal acceleration, and deviation from "On Speed" angle of attack respectively. The FPM and CDM are referenced against the ARP, while the climb-dive ladder, longitudinal acceleration cue, and speed worm are referenced against the CDM.

One of the features of existing HUDs which has contributed to the hesitance of man to adopt it as a primary flight reference is the lack of stability of the flight path marker as a primary control reference as opposed to tradition pitch reference attitude references. The FPM, unlike the fixed pitch reference, tends to be much more dynamic within the field-of-view of the HUD. Much the dynamic qualities of the FPM is due to the transient increases in AO/A during variable pitch rate maneuvering resulting from the inertial lags of the velocity vector relative to the aircrafts pitch attitude. This resultant lag in the velocity vector causes a depression of the FPM in the IFOV of the HUD. During highly dynamic maneuvering, this displace can often render the FPM useless as a control reference.

For example, the displacement of the FPM can cause two undesirable side effects. First, the displacement of the FPM also displaces all the symbols that are positioned relative to the FPM (i.e., ILS/TACAN symbolgy, Climb/Dive Ladder). The motion and displacement of the symbolgy make the HUD symbolgy more difficult to read. Second, the displacement of the FPM by the transient AOA may cause the pilot to overshoot a desired climb-dive angle.

To overcome these problems, the position of the CDM is "quicken" by adding a lead factor into its position. The goal of this "quicken" term is to filter out the transient AOA. The result is stability in the positioning of the CDM and its related symbolgy. Also, during pitching maneuvers, the position of the CDM more accurately represents the final (i.e., after the AOA transient) position. However, a side effect of this lead factor is that "quicken" CDM no longer accurately represents the true instantaneous climb-dive angle.

Section 6 explains the details of the algorithms used to 'quicken' the CDM and FPM.

2.1. CLIMB DIVE ANGLE MARKER

The Climb-Dive Angle Marker (CDM), shown in Figure 2-2, displays the current climb-dive angle when read against climb-dive ladder. The CDM symbol is horizontally fixed to the centerline of the IFOV but is free to move vertically within the limits of the IFOV. The CDM is removed whenever it is limited and the dashed CDM is displayed in its place. A description of the equations used to quicken and position the CDM is provided in Section 6.

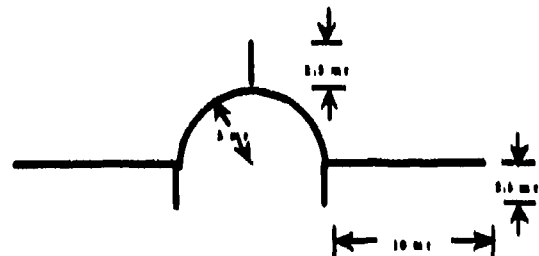


Figure 2-2 -- Climb-Dive Angle Marker (CDM)

The dashed CDM, shown in Figure 2-3, is displayed whenever the CDM is limited.

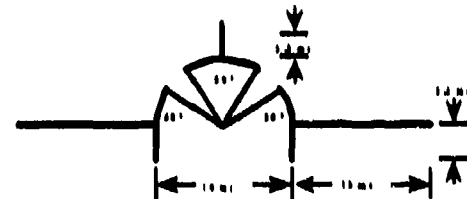


Figure 2-3 -- Dashed Climb-Dive Angle Marker

2.2. FLIGHT PATH MARKER

The Flight Path Marker (FPM), shown in Figure 2-1, indicates the actual flight path of the aircraft when read against the outside world. The symbol is quickened and is free to move within the limits of the entire TFOV. See Section 6 for the FPM's quickening and position equation.

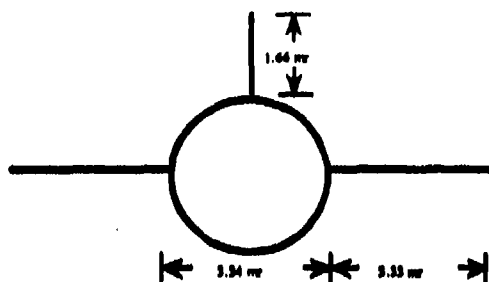


Figure 2-1 - Flight Path Marker

2.3. CLIMB DIVE LADDER

The Climb-Dive Ladder (CDL) displays the aircraft's climb-dive and roll angle when read against the CDM. The CDL is a continuous scale consisting of the true and ghost horizon lines, climb-dive bars with numerical labels, the zenith and nadir symbols, and the glideslope reference bar. See Section 6 for the CDL's quickening and position equations.

The spacing of the CDL bars is compressed at a variable rate from a 1:1 ratio to a 4.4:1 ratio. The horizon line and the 5 degree climb/dive bar are spaced at a 1:1 relationship with the outside world. The compression ratio then increases linearly to a 4.4:1 ratio at the 90 degree zenith/nadir symbol. See Section 7 for details on the compression of the Climb-Dive Ladder.

2.3.1. Horizon Line

The Horizon Line (HL) is used with the CDL scale at the zero climb-dive angle position to provide a horizontal reference point. The Horizon Line is a bold line that extends the entire width of the HUD TFOV with a 32 mr gap in the center and is occluded by the speed and altitude scales. The horizon line is displayed whenever it is within the limits of a circle contained within the IFOV. Otherwise, the ghost horizon line is displayed. In the CSEF HUD, this circle has a radius of 100 mr which was determined by the IFOV restrictions of the CSEF's Block 25 HUD.

The Ghost Horizon Line (GHL) provides a horizon reference any time the true horizon line is outside the limits of the IFOV. The GHL is a bold, dashed line extending the entire width of the HUD TFOV. The line is positioned on the tangent of a circle about the CTFOV and parallel to the horizon. Whenever the CDM is near the GHL, the radius of the circle is increased to maintain a minimum distance of 20 mr between the CDM and GHL.

2.3.2. Climb-Dive Bars

The Climb-Dive Bars make-up the CDL to display the aircraft's climb-dive angle when read against the CDM. The Climb-Dive Bars consist of 11 solid climb bars and 11 dashed dive bars. The bars are positioned at 5 degree intervals from 5 to 30 degrees and 10 degree intervals from 40 to 80 degrees.

To help distinguish between the climb and dive portions of the CDL, the climb bars are tapered and the dive bars are bent. The length of the wings on the climb bars are tapered linearly from full length at the 5 degree climb bar down to 30% of length at the 80 degree bar. The wings on the dive bars are bent or sloped by one-half of the dive angle.

2.3.2.1. Climb Bars

The Climb Bars display the aircraft's climb angle when read against the CDM. The horizontal lines of the bars are tapered linearly from full length at the 5 degree bar down to 30% of length at the 80 degree bar. The following equation gives the percentage of full length for each of the climb bars.

$$\text{Angle}_{\text{climber}} = \text{Climb Bar Angle in degrees}$$

$$\% \text{ FullLength} = 100 - \frac{14}{15} (\text{Angle}_{\text{climber}} - 5)$$

The full length 5 degree climb bar consists of two 30 mr lines separated by a 32 mr gap and with 5 mr vertical lines extending off each end. Numerical labels ranging from 5 to 80 are located on the lower left side of the respective climb bars. Examples of the 5 degree and 80 degree climb bars are shown in Figures 2-4 and 2-5, respectively.

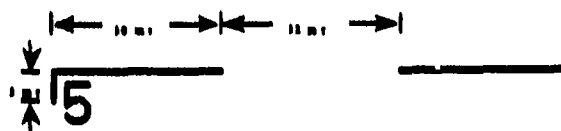


Figure 2-4 -- 5 Degree Climb Bar

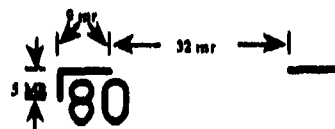


Figure 2-5 -- 80 Degree Climb Bar

2.3.2.2. Dive Bars

The Dive Bars display the aircraft's dive angle when read against the CDM. The dive bars consist of two 30 mr dashed lines separated by a 32 mr gap. The bars are bent by one-half of the dive angle (e.g., the 40 degree dive bar has 20 degrees of slope). Numerical labels ranging from -5 to -80 are located on the upper left side of the respective dive bars. Examples of the 5 degree and 80 degree dive bars are shown in Figures 2-6 and 2-7, respectively.

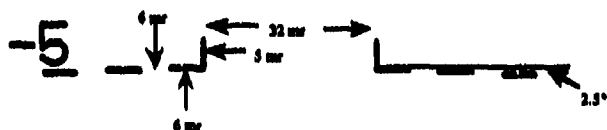


Figure 2-6 -- 5 Degree Dive Bar

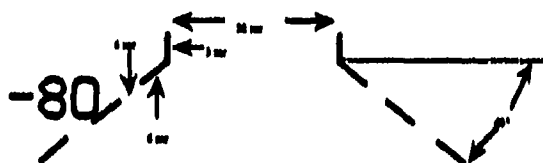


Figure 2-7 -- 80 Degree Dive Bar

2.3.3. Zenith Symbol

The zenith symbol, shown in Figure 2-8, displays the highest possible climb angle (i.e., 90 degree climb angle). The zenith symbol is always rotated to point toward the nearest horizon.

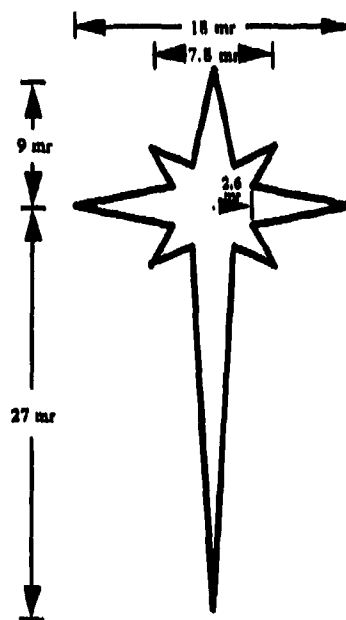


Figure 2-8 -- Zenith Symbol

2.3.4. Nadir Symbol

The nadir symbol, shown in Figure 2-9, displays the lowest possible dive angle (i.e., 90 degree dive angle). The nadir symbol is always rotated to point toward the nearest horizon.

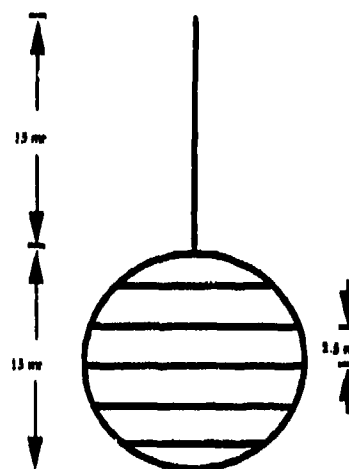


Figure 2-9 -- Nadir Symbol

2.3.5. Glideslope Reference Bar

The glideslope reference bar, shown in Figure 2-10, is used by the CDL as a glideslope reference and appears whenever the aircraft is in ILS mode. The bar is

positioned at the glideslope angle or 2.5 degrees below the horizon line.

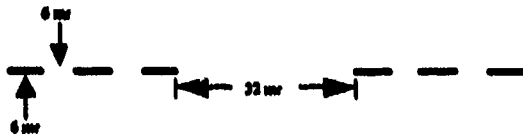


Figure 2-10 -- Glideslope Reference Bar

2.4. LONGITUDINAL ACCELERATION CUE

The Longitudinal Acceleration Cue (LAC), when read against the CDM, provides an indication of the aircraft's acceleration (velocity) along its flight path. The LAC is displayed when the HUD is in ILS mode or landing gear is down. The cue, shown in Figure 2-11, is positioned to the left of the CDM and its vertical movement is limited to 4.5 degrees above and below the wing of the CDM. The following set of equations describes the mechanization of the LAC.

$Acc = \text{Aircraft's Longitudinal Acceleration in Gs}$

$Acc_{cue} = \text{Longitudinal Acceleration Cue Position}$

$Acc_{cue} = Acc \times 9.0 \quad \text{lim}[-4.5, 4.5]$

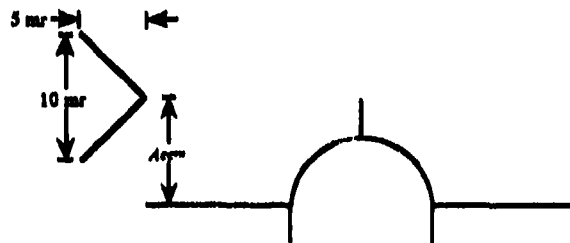


Figure 2-11 -- Longitudinal Acceleration Cue

2.5. SPEED WORM

The Speed Worm, shown in Figure 2-12, indicates deviation from the aircraft's "On Speed" Angle of Attack. This symbol is located on the left wing of the CDM and remains vertical in relation to the CDM. The worm is a rectangle that varies in height above or below the CDM wing. The Speed Worm is displayed when the HUD is in ILS mode or landing gear is down. The following set of equations describes the mechanization of the Speed Worm.

$\alpha_{spd} = \text{On Speed Angle Of Attack}$

$\alpha = \text{Aircraft's Angle Of Attack}$

$SpeedWormHeight = [\alpha_{spd} - \alpha] + 4.0 \quad \text{lim}[-1.0, 1.0]$

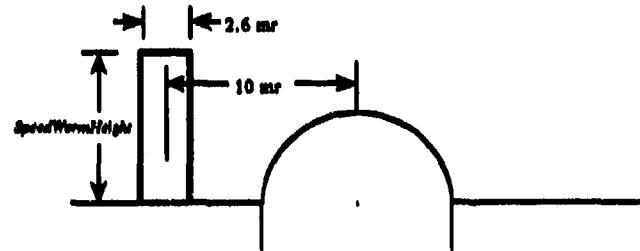


Figure 2-12 -- Speed Worm

3. SCALES

The HUD scales are used to display the aircraft's speed, barometric altitude, radar altitude, heading, and roll. All scales, except the roll scale, are positioned against the left and right hand reference points (LHRP and RHRP). The roll scale is centered around the CTFOV.

3.1. SPEED SCALE

The speed scale, shown in Figure 3-1, displays the aircraft's current and commanded speeds. The speed scale consists of a dial with index, commanded speed caret and various readouts. The readouts include the current speed, commanded speed, ground speed, mach number, and vertical acceleration. The type of speed is selectable between calibrated, true, or ground speeds -- the selection mechanism is aircraft dependent. The center of the speed dial is at the LHRP.

The current speed is displayed as a digital readout at the center of the dial. A single, full size character, 'T' or 'G', is displayed below the readout to indicate either true airspeed or ground speed, respectively, has been selected. No character is displayed whenever calibrated airspeed is selected.

The commanded speed readouts are displayed above the dial whenever the difference between the current speed and the commanded speed is greater than 40 knots. The commanded speed caret is displayed on the dial whenever the aircraft's speed is within 40 knots of the commanded speed. In the CSEF mechanization, the commanded speed is approach speed.

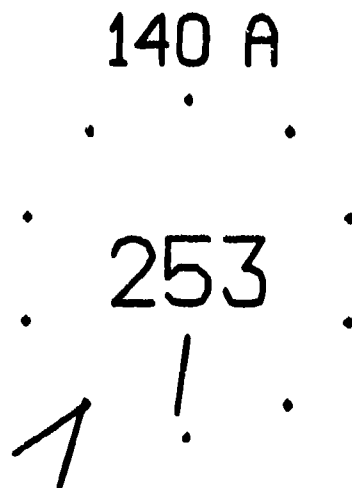


Figure 3-1 - Speed Scale

3.1.1. Speed Dial

The speed dial, shown in Figure 3-2, consists of 10 dots equally spaced around an 18 mr circle and an 7 mr index located 9 mr from the center of the dial. The index makes one complete clockwise revolution for every 100 knots of increasing speed. The center of the speed dial is at the LHRP.

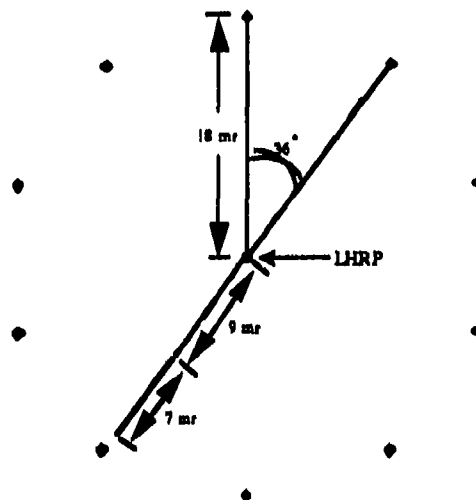


Figure 3-2 - Speed Dial

3.1.2. Speed Readout

The speed readout, composed of three digits, is displayed in the center of the speed dial. All digits are full size (7 mr high by 4 mr wide) and leading zeroes are displayed as blank spaces. The resolution of the display is to the nearest knot.

999

3.1.3. Commanded Speed Caret

The commanded speed caret points to the commanded speed whenever the difference between the current speed and the commanded speed is less than 40 knots. The caret is located on the outside edge of the speed dial and points inward.

A 60% sized letter appears next to the caret to identify which commanded speed is being indicated by the caret. In the CSEF mechanization, the commanded speed is approach speed, which is identified by the letter 'A'.

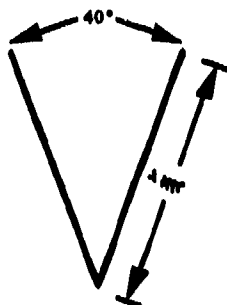


Figure 3-4 - Commanded Speed Caret

3.1.4. Commanded Speed Readouts

The commanded speed readouts display the various commanded speeds. A readout is displayed whenever the difference between the current speed and the commanded speed is greater than 40 knots. The readouts are positioned above the speed dial.

In the CSEF mechanization, the only commanded speed is approach speed which is displayed in ILS mode. It is composed of three digits followed by the letter 'A'. All digits are 60% of full size and leading zeros are displayed as blank spaces. The resolution of the display is to the nearest knot. The lower left edge of the readout is positioned 40 mr above and 15 mr left of the LHRP.

140 A

3.1.5. Ground Speed Readout

The ground speed readout displays the current aircraft ground speed to the nearest knot. The readout consists of the letter 'G', a blank space, and a 3 digit number. The characters are all full size and leading zeros are displayed as blank spaces. In the CSEF HUD, the lower left edge of the readout is positioned 50 mr below and 25 mr right of the LHRP.

G 540

3.1.6. Mach Number Readout

The mach number readout displays the current aircraft mach number. The readout consists of the letter 'M', a blank space, and a 3 digit number with 2 digits right of the decimal point. The characters are all full size and if

the leading digit is a zero then it is displayed as a blank space. In the CSEF HUD, the mach number readout is positioned 10 mr below the ground speed readout.

M 1.20

3.1.7. Vertical Acceleration Readout

The vertical acceleration readout displays the current aircraft vertical acceleration in G's. The readout consists of a number followed by the letter 'G'. The number consists of a minus sign, two digits, a decimal point, and one digit right of the decimal point. The characters in the number are all full size but the letter 'G' is 60% of full size. If the leading digit is a zero then it is displayed as a blank space. The vertical acceleration readout is positioned 10 mr below the mach number readout.

1.0G

3.2. ALTITUDE SCALE

The altitude scale, shown in Figure 3-9, displays the aircraft's current and commanded altitudes and the aircraft's vertical velocity. The altitude scale consists of a dial with an index, altitude readout, commanded altitude caret, commanded altitude readouts, and a vertical velocity arc. The commanded altitude caret is displayed whenever the aircraft's altitude is within 400 ft of the commanded altitude and the vertical velocity arc is displayed whenever the CDM is limited. The altitude dial is positioned at the RHRP.

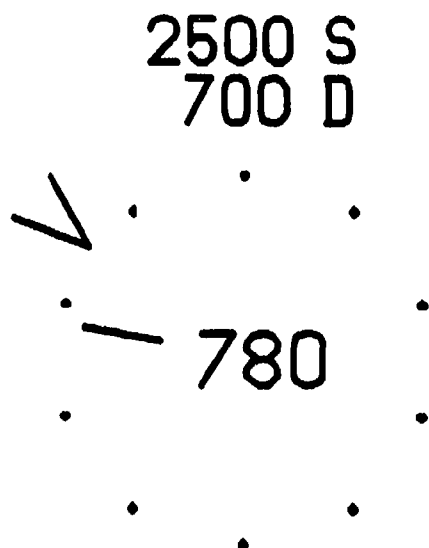


Figure 3-9 - Altitude Scale

3.2.1. Altitude Dial

The altitude dial, shown in Figure 3-10, consists of 10 bold dots equally spaced around a 25 mr circle and an 10.5 mr index located 12.5 mr from the center of the dial. The index makes one complete clockwise revolution for every 1000 feet of increased altitude. The center of the dial is at the RHRP.

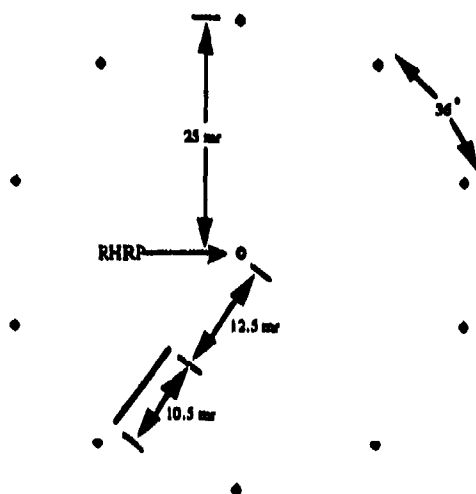


Figure 3-10 - Altitude Dial

3.2.2. Altitude Readout

The altitude readout, composed of five digits, is displayed at the center of the altitude dial. Whenever the aircraft's altitude is greater than or equal to 10,000 ft, the two leading digits (thousands) are displayed full size

(7 mr high by 4 mr wide) and the remaining three digits (hundreds, tens and units) are displayed at 60% of full size.

10000

When the aircraft's altitude is less than 10000 ft, all the digits are displayed full size. Leading zeroes are displayed as blank spaces. The resolution of the display is to the nearest foot.

9999

3.2.3. Commanded Altitude Caret

The commanded altitude caret, shown in Figure 3-13, points to the commanded altitude whenever the difference between the current altitude and the commanded altitude is less than 400 feet. The caret is located on the outside edge of the altitude dial and points inward.

A 60% sized letter appears next to the caret to identify which commanded altitude is being indicated by the caret. In the CSEF mechanization, the commanded altitudes are the step-down altitude, which is identified by the letter 'S', and the decision height altitude, which is identified by the letter 'D'.

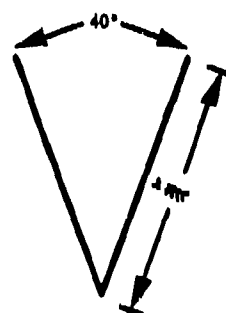


Figure 3-13 - Commanded Altitude Caret

3.2.4. Commanded Altitude Readouts

The commanded altitude readouts display the various commanded altitudes. A readout is displayed whenever the difference between the current altitude and a commanded altitude is greater than 400 feet. The readouts are positioned above the altitude dial.

In the CSEF mechanization, the commanded altitudes are step-down altitude and decision height that are displayed in ILS mode. The step-down altitude readout is composed of four digits followed by the letter 'S'. The decision height readout consists of four digits followed by the letter 'D'. All digits are 60% of full size and leading zeroes are displayed as blank spaces. The resolution of the display is to the nearest foot. The step-down readout is positioned 50 mr above and 10 mr left of the RHRP. The decision height readout is positioned 10 mr below the step-down readout.

1500 S
600 D

3.2.5. Vertical Velocity Arc

The vertical velocity arc displays the aircraft's vertical velocity when read against the altitude dial. The vertical velocity arc is a bold arc that is displayed whenever the CDM is limited. The vertical velocity arc is limited to ± 4000 ft/sec. During a climb, the amount of vertical velocity is displayed by a bold arc that starts at the 9 o'clock position (750 ft) and extends in the clockwise direction along the upper arc of the altitude dial -- during a dive, it extends in the counter-clockwise direction along the lower arc.

The following table shows how far the vertical velocity arc extends around the altitude dial for a given climb rate. The arc starts at the 9 o'clock position and is drawn in the clockwise (CW) direction.

<u>Climb Rate</u>	<u>Altitude Dial Position</u> <u>(CW direction)</u>
Level Flight	750 ft (9 o'clock)
1000 ft/sec	900 ft dot
2000 ft/sec	0 ft dot
3000 ft/sec	100 ft dot
4000 ft/sec	200 ft dot

The following table shows how far the vertical velocity arc extends around the altitude dial for a given dive rate. The arc starts at the 9 o'clock position and is drawn in the counter-clockwise (CCW) direction.

<u>Dive Rate</u>	<u>Altitude Dial Position</u> <u>(CCW direction)</u>
Level Flight	750 ft (9 o'clock)
1000 ft/sec	600 ft dot

2000 ft/sec	500 ft dot
3000 ft/sec	400 ft dot
4000 ft/sec	300 ft dot

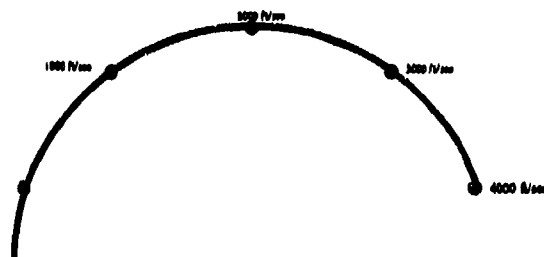


Figure 3-16 Vertical Velocity Arc

3.3. RADAR ALTITUDE SCALE

The radar altitude scale, shown in Figure 3-17, displays the aircraft's radar altitude. The radar altitude scale consists of a thermometer scale, vertical column that changes in length with altitude, and a minimum descent altitude bar. The thermometer scale is a series of tick marks representing 0 to 1500 feet of altitude. The vertical column, located just left of the thermometer scale, indicates radar altitude when read against the scale. The low altitude bar indicates the selected low altitude setting and is located on the left side of the thermometer scale. The radar altitude scale is located to the left of the altitude scale. In the CSEF HUD, the bottom of the scale is located 40 mr to the left and 45 mr down from the RHRP.

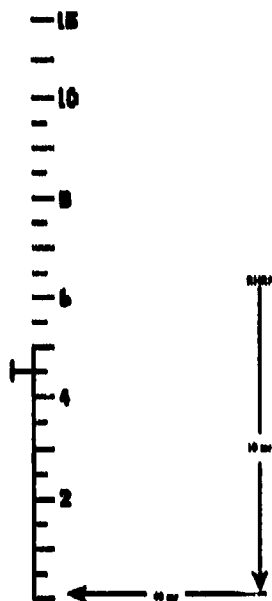


Figure 3-17 - Radar Altitude Scale

3.3.1. Thermometer Scale

The thermometer scale, shown in Figure 3-18, consists of tic marks every 50 feet from 0 to 1000 ft. The tic marks at the 100 foot intervals are 3 mr in length and the marks at the 50 foot intervals are 1.2 mr in length. Beyond the 1000 ft tic mark, two additional tic marks represent 1250 and 1500 ft. Numerical labels on the right side of the scale indicate radar altitude in hundreds of feet. The aircraft's radar altitude is displayed by a vertical column that moves along the left side of the scale. The bottom of the column is anchored at the base of the thermometer scale, while the top moves along the left side of the thermometer scale and indicates the aircraft's radar altitude when read against the scale.

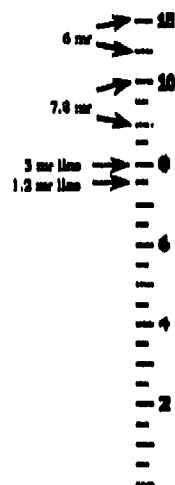


Figure 3-18 - Thermometer Scale

3.3.2. Minimum Descent Altitude Bar

The Minimum Descent Altitude (MDA) bar, shown in Figure 3-19, indicates the radar altitude the aircraft should not descend below. The MDA bar is displayed on the left side of the thermometer scale and the method of setting the MDA is dependent on the aircraft.

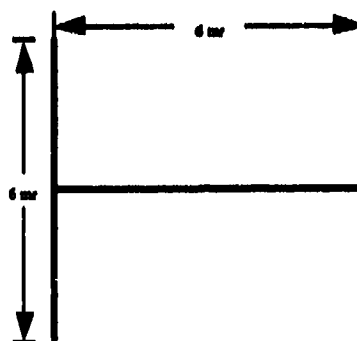


Figure 3-19 -- MDA Bar

3.4. HEADING SCALE

The heading scale, shown in Figure 3-20, indicates the aircraft's magnetic heading and consists of a horizontal scale and a lubber line. The lubber line indicates the aircraft's magnetic heading when read against the horizontal scale. The center point of the heading scale is located above the midpoint of a line connecting the LHRP and RHRP. In the CSEF HUD, the scale is positioned 65 mr above the midpoint.

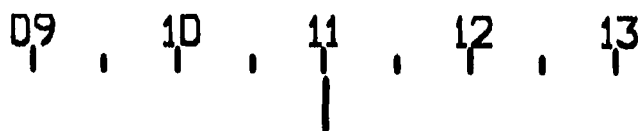


Figure 3-20 -- Heading Scale

3.4.1. Horizontal Heading Scale

The horizontal heading scale, shown in Figure 3-21, is a continuous scale that moves left and right indicating aircraft heading when read against fixed lubber line. The scale consists of 5 mr, vertical tic marks every 10 degrees and 3 mr, vertical tic marks every 5 degrees. A minimum of 30 degrees are displayed and the scale is compressed at a 5:1 ratio. Two digit numeric labels that range from 01 to 36 are positioned above the 10 degree tic marks indicating 10 to 360 degrees of heading.



Figure 3-21 -- Horizontal Heading Scale

3.5. ROLL SCALE

The roll scale, shown in Figure 3-22, displays the aircraft's roll and sideslip. The roll scale consists of a curved roll scale drawn around the CTFOV and a roll/sideslip arrow.



Figure 3-22 -- Roll Scale with 20° roll (right wing down)

3.5.1. Curved Roll Scale

The curved roll scale consists of a center index and three tic marks at 10 degree intervals on either side of the index representing 10, 20, and 30 degrees of aircraft roll. When the aircraft's roll angle is greater than 25 degrees, additional tic marks are displayed at the 45 degree and 60 degree positions on the same side of the scale as the roll/sideslip arrow. Likewise, when the roll angle is greater than 55 degrees, additional tic marks are drawn at the 90 degree and 135 degree positions.

The radius of the roll scale is 70 mr and is centered about the CTFOV. If the CDM comes within 20 mr of the zero roll index, the roll scale is lowered to maintain the 20 mr.

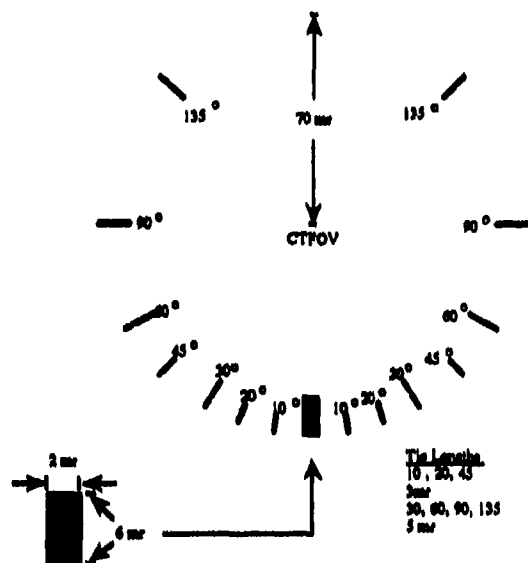


Figure 3-23 - Curved Roll Scale

3.5.2. Roll/Sideslip Arrow

The roll/sideslip arrow is divided into two sections: a triangle shaped upper section and a trapezoid shaped lower section. The upper section indicates the magnitude and direction of roll when read against the curved roll scale. The lower section indicates the magnitude and direction of aircraft sideslip when read against the upper section.

When the aircraft is at wings level flight, the roll/sideslip arrow is positioned below the center index of the curved roll scale -- the tip of the arrow touching the bottom of the center index of the scale. As the aircraft rolls in the clockwise direction (right wing down), the arrow moves an equal number of degrees around the curved scale in the counter-clockwise direction; likewise for a left wing down roll. The arrow has unlimited 360 degree movement about the CTFOV and is rotated for all roll angles to point toward the CTFOV.

The lower section is positioned relative to the upper section by the amount of sideslip. For example, with 30 degrees of right roll and a sideslip of 3 degrees to the

right, the upper section will be rotated to the 30 degree
tic and the lower section will be rotated 33 degrees.

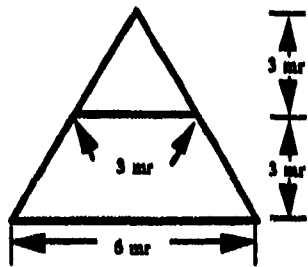


Figure 3-24 - Roll/Sideslip Arrow

4. NAVIGATIONAL SYMBOLOGY

The navigational symbology provides the pilot with location and steering information to return to a designed flight path or course. The symbology consists of a Course Deviation Indicator (CDI), a Vertical Deviation Indicator (VDI), flight director steering bars, and a TACAN Indicator. The CDI, VDI, and steering bars are located relative to the CDM. The TACAN indicator is positioned relative to the CTFOV.

4.1. COURSE DEVIATION INDICATOR (CDI)

The Course Deviation Indicator (CDI), shown in Figure 4-1, displays the selected course and the magnitude and direction of deviation. The indicator is centered around the CDM and consists of a scale and a pointer. The CDI is displayed in both TACAN and ILS modes.

The selected sensor source readout and a digital course readout are located in the lower left hand corner of the HUD (see Sections 5.1 and 5.2). In the CSEF mechanization, the sensor sources include TACAN and ILS.

The scale consists of four dots with a maximum of 2 dots being displayed at any instance. The pointer is read against the CDM and CDI scale. The pointer and scale rotate about the CDM to indicate the selected course.

Two types of pointers are used. The standard (unbroken) pointer is used when the course deviations are greater than one dot. The broken pointer is used when the deviations are less than or equal to one dot. The break in the pointer is used to prevent obstruction of the CDM symbol.



Figure 4-1 -- Course Deviation Indicator (CDI)

4.1.1. CDI Scale

The CDI scale, shown in Figure 4-2, contains four 3 mr circles, or dots, with a maximum of 2 dots being displayed at any instance. On either side of the scale, the inner two dots are located 15 mr from the center and each outer dot located another 15 mr from the inner dot. The CDI scale centered upon the CDM and is free to rotate a full 360 degrees about the CDM.

When the deviation is more than 1 1/2 dots, two dots are shown on the same side of the CDM as the CDI pointer. When the deviation is between 1/2 and 1 1/2 dots, the inner 2 dots on each side of the CDM are shown. No dots are shown when the deviation is less than 1/2 dot.

The amount of deviation represented by each dot is mode dependent: 5 degrees per dot for TACAN and 0.35 degrees per dot for ILS localizer.

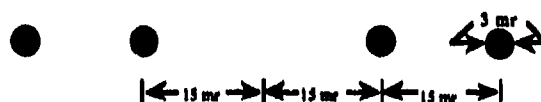


Figure 4-2 -- CDI Scale

4.1.2. CDI Pointer

The unbroken CDI pointer, shown in Figure 4-3, indicates course deviation when read against the CDI scale. It is displayed whenever the CDI deviation is greater than one dot, otherwise the broken CDI pointer is displayed.

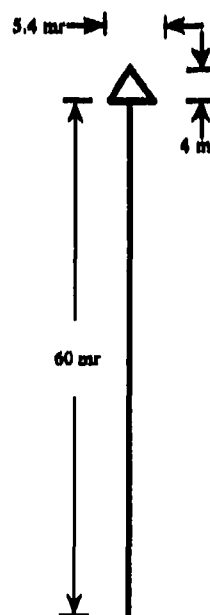


Figure 4-3 -- Unbroken CDI Pointer

The broken CDI pointer, shown in Figure 4-4, indicates course deviation when read against the CDI scale. It is displayed whenever the CDI deviation is less than or equal to one dot, otherwise the unbroken CDI pointer is displayed. The 40 mr gap prevents the CDM from being obscured.

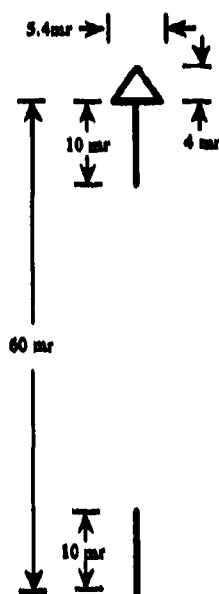


Figure 4-4 -- Broken CDI Pointer

4.2. VERTICAL DEVIATION INDICATOR (VDI)

The Vertical Deviation Indicator (VDI), shown in Figure 4-5, displays the magnitude and direction of the aircraft's vertical deviation from the desired glidepath. In the CSEF mechanization, ILS glideslope is the only source of commanded flight path and the VDI is displayed only in ILS mode.

The indicator consists of a scale and a pointer. The pointer is read against the scale. For ILS glideslope, one dot of pointer deflection represents 0.35 degrees of glideslope deviation.

The VDI is located to the right of the CDM and moves vertically with it. In the CSEF HUD, the VDI is positioned 70 mr to the right of the CDM.

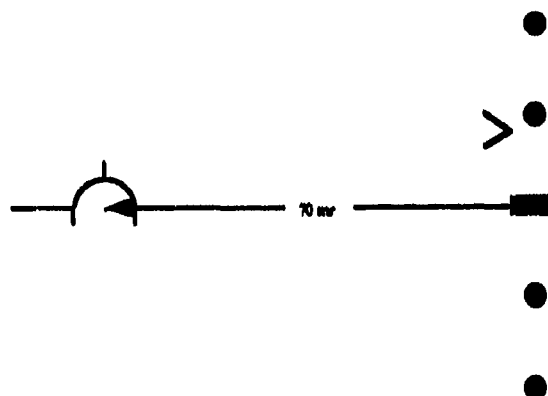


Figure 4-5 -- Vertical Deviation Indicator

4.2.1. VDI Scale

The VDI scale, shown in Figure 4-6, is used in conjunction with the VDI pointer to indicate vertical deviation. The scale consists of four 3 mr circles, or dots, and a 6 mr by 2 mr, open centered box. The dots are located two above and two below the box.

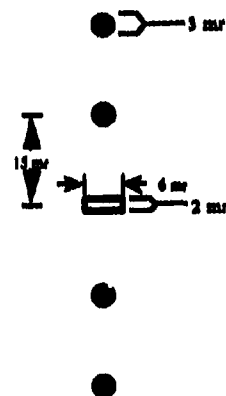


Figure 4-6 -- VDI Scale

4.2.2. VDI Pointer

The VDI pointer, shown in Figure 4-7, indicates vertical deviation when read against the VDI scale. The pointer is located on the left side of the VDI scale pointing to the right.

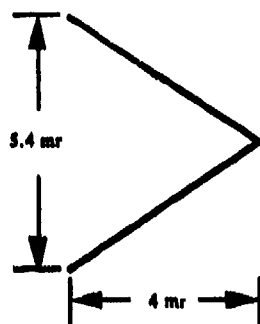


Figure 4-7 -- VDI Pointer

4.3. FLIGHT DIRECTOR STEERING BARS

The two flight director steering bars, bank steering and pitch steering, indicate the amount and direction of the flight director roll and pitch steering error, respectively, when read against the CDM. As the pilot rolls and pitches in the direction of the bars, the steering errors decrease and the bars move toward the CDM. The aircraft is at the commanded roll and pitch angle when the bars are positioned on the CDM. Both bars are 80 mr in length and are displayed whenever the HUD is in ILS mode. The movement of the bars is limited to ± 2.5 degrees.

The flight director steering bars are shown in figure 4-8. In this example, the pilot is being directed to pitch up and roll to the right.

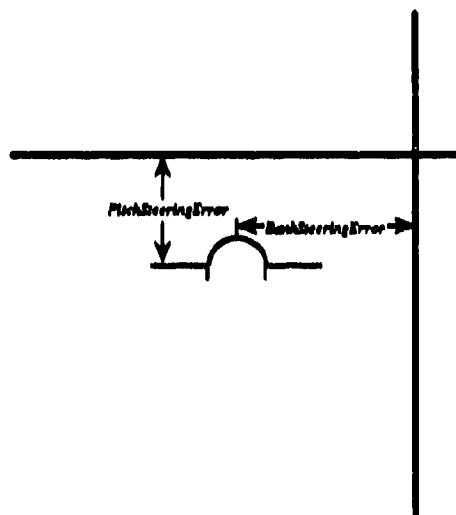


Figure 4-8 -- Flight Director Steering Bars

4.4. TACAN INDICATOR

The TACAN indicator, shown in Figure 4-9, displays the relative bearing to the selected TACAN station and the radial from the station. The pointer consists of a bearing pointer, reference wings, and a readout. The pointer moves about the center of the indicator to show the relative, magnetic bearing to the TACAN station. The readout displays the magnetic radial from the station. The pointer is removed and the readout will display XXX whenever the TACAN radio is not receiving a signal.

The indicator is displayed in TACAN and ILS modes and is located in the upper left corner of the IFOV. In the CSEF HUD, the center of the indicator is 100 mr right and 137 mr above the CTFOV.

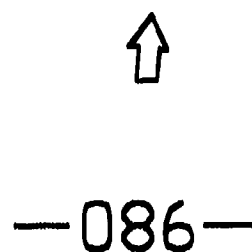


Figure 4-9 -- TACAN Indicator

4.4.1. Bearing Pointer

The bearing pointer, shown in Figure 4-10, displays the relative bearing to the selected TACAN station. The pointer is located 20 mr from the center of the TACAN bearing indicator and is free to rotate a full 360 degrees about the center. If the TACAN radio is not receiving a signal from a station, then the pointer is not displayed.

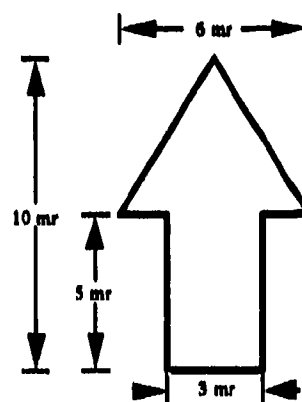


Figure 4-10 -- Bearing Pointer

4.4.2. Reference Wings

The bearing pointer reference wings, shown in Figure 4-11, display a reference point against which the bearing pointer can be read. The wings consist of two 8 mr horizontal bars that represent the aircraft's wings. The bars are located 10 mr from the center of the indicator.

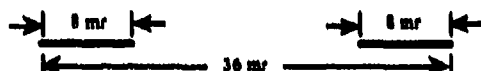


Figure 4-11 -- Reference Tics

4.4.3. TACAN Radial Readout

This readout, shown below, displays magnetic radial from the selected TACAN station to the nearest degree. The readout consists of a 3 digit number with the leading zero shown. The readout will display XXX whenever the TACAN radio is not receiving a signal. The readout is located at the center of the TACAN bearing indicator.

086 or XXX

5. TEXT READOUTS

Two groups of text readouts appear, one on each side of the HUD. The left side includes CDI sensor and course readouts. The right side includes TACAN DME, TACAN channel number, and time readouts. The readouts are located inside the lower left and lower right corners of the IFOV and do not move with the left and right hand reference points. In the CSEF HUD, the readouts are referenced from the CTFOV.

5.1. CDI SENSOR SOURCE

CDI sensor source is a 3 character readout that displays the selected sensor source for the CDI display. Currently, two sensors are defined: 'ILS' and 'TCN'. The readout is located in the lower left corner of the IFOV. In the CSEF HUD, the readout is positioned 120 mr left and 90 mr below the CTFOV.

ILS or TCN

5.2. CDI COURSE

This readout displays the CDI course to the nearest degree. The readout is used in conjunction with the CDI display and consists of a 3 digit number ranging from 1 to 360. Leading zeros are displayed. The course readout is located to the right of the navigational mode readout. In the CSEF HUD, the readout is positioned 96 mr left and 90 mr below the CTFOV.

360

5.3. TACAN DME READOUT

This readout, which is used in conjunction with the TACAN Bearing Indicator, displays the TACAN DME to the nearest one-tenth nautical mile. The readout consists of a 4 digit number with one digit right of the decimal point. Leading zeros are displayed as blank spaces. The TACAN DME readout is located in the lower right corner of the IFOV. In the CSEF HUD, the readout is positioned 70 mr right and 80 mr below the CTFOV.

999.9

5.4. TACAN CHANNEL

This readout, which is used in conjunction with the TACAN Bearing Indicator, displays the TACAN channel number. The readout consists of the label 'CH', a 3 digit channel number, and an 'X' or 'Y' indicating which TACAN band. Leading zeros on the channel number are displayed as blank spaces. The TACAN channel readout is located to the right of the TACAN DME readout. In the CSEF HUD, the readout is positioned 106 mr right and 80 mr below the CTFOV.

CH_90X

5.5. TIME READOUT

This readout displays a time to the pilot. The time is mission dependent and may include time to steerpoint, time to impact, or time to release. The readout consists of a 3 digit readout displaying minutes and a 2 digit readout displaying seconds, with a colon separating the two readouts. Leading zeros on the minutes readout is displayed as blank spaces. The time readout is displayed directly below the TACAN DME readout. In the CSEF HUD, the readout is positioned 70 mr right and 90 mr below the CTFOV.

123:45

5.6. ALTIMETER SETTING

This readout displays the current barometric pressure setting for the altimeter. The altimeter setting readout consists of 4 digit number with two digits right of the decimal point. The altimeter setting readout is located below the time readout. In the CSEF HUD, the lower left edge of the readout is positioned 82 mr right and 100 mr below the CTFOV.

29.92

6. POSITIONING AND QUICKENING OF THE CDM, FPM, AND CDL

6.1. QUICKENING.

Quickening is a means of compensating for the effects of inertial lag by calculating an estimate of the CDM displacement CDM caused by these lags. Evaluations conducted by the Naval Air Test Center concluded that during approach and landing, a washed-out pitch attitude lead term results in superior performance while a pitch rate lead term is more appropriate for the highly dynamic maneuvers occurring during up-and-away flight.

Take for example, a situation where the pilot is on approach and is below the desired glideslope. The pilot makes an appropriate nose-up correction to reduce the rate of descent. Initially, both the ladder and FPM will dip downward in the display reflecting the pitch attitude change resulting from the control input. This is not a delay in the display but rather the effect of aircraft inertia causing flight path to lag instantaneous changes in pitch attitude.

Once the pilot achieves the desired pitch attitude and terminates the control input. The FPM, overcoming the effect of inertia, continues to rise stabilizing approximately one second after the control input was terminated. Under such conditions, the pilot is required to lead the FPM to achieve the desired flight path angle and prevent control overshoots. If the pilot fails to lead compensate the FPM, he become susceptible to pilot induced oscillation and potential loss of situational awareness.

During up and away flight, the problem is of a different nature in that the dramatic changes in AOA which can occur during the hard-g maneuvering required during air-to-air engagements can cause the FPM virtually unusable as an attitude reference. The implementation of a body-axis pitch rate lead filter as a compensation to the FPM during such maneuvers can drastically reduce the dynamic nature of the FPM or CDM making it a more interpretable reference.

The provisional HUD standard incorporates both forms of display quickening.

Pitch washout, Q_1 , is used to quicken the FPM and CDL at low pitch angles and to quicken the CDM in ILS mode or landing gear down. Pitch rate lead, Q_2 , is used to quicken the CDM in normal flight and to quicken the FPM, CDL, and CDM, in landing mode, at high pitch angles.

The following set of equations defines the quickening terms Q_1 and Q_2 ...

θ = Aircraft Pitch Angle

ϕ = Aircraft Roll Angle

θ_1 = Aircraft Pitching Rate, aircraft axis

G_1, G_2 = quickener gains

$$Q_1 = G_1 \cos \phi \frac{\tau s}{\tau s + 1} \theta \quad \text{-- Pitch Washout}$$

$$Q_2 = G_2 \frac{\tau}{\tau s + 1} \theta_1 \quad \text{-- Pitch Rate Lead}$$

... where s is the La place complex frequency variable, and τ is the time constant that controls the rate of washout.

According to research conducted by the Royal Aerospace Establishment, in fighter type aircraft, the time constant τ may be assumed to vary as:

$$\tau = A + \frac{B}{V_1 \sigma}$$

Where: A and B are constants

V_1 is the aircraft's true airspeed

and

σ is the relative density ratio

6.1. 1. Tuning of the Time Constant

It remains to determine the optimum values for both A and B which provide the best match between the quickener and the dynamic characteristics of the aircraft over the full flight envelope and range of configurations and masses of the vehicle.

The method proposed here was originally adopted and implemented by the engineers at the Royal Aerospace Establishment, Bedford England (Hall and Penwill, 1989) and is as follows:

- 1 Determine τ at two flight condition widely separated in v, σ (See section on Tuning of Time Constant)

For the CSEF F-16 simulator the flight conditions chosen were:

- i) A representative normal attack speed and configuration (i.e., 400 knots at 1000 to 2000 ft)
- ii) Slow speed (i.e., 250 knots at 1000 to 2000 ft)

- 2 Determine A and B from the two values of τ so defined

- 3 Check the operation of the Quickener so defined at alternative speeds, heights, aircraft configurations and aircraft masses to ensure that the value of τ is adequately predicted over the full flight envelope of the vehicle.

The process of tuning the quickener time constant requires the following facility capabilities

a) Time Constant

The time constant should be programmed to vary as

$$\tau = A + B/(v, \sigma) + \Delta\tau$$

where $\Delta\tau$ is used during the tuning process to vary τ . This method of adjusting τ compensates for small errors in speed and height during the aircraft maneuvers used to tune the quickener.

The operator must be able to change the values of A , B and $\Delta\tau$ while the simulator is flying.

b) Quickener Gain

The operator must be able to change the value of the quickener gain while the simulator is flying. In particular, the operator must be able to change the quickener gain between 0.7 and 1.0.

c) Fixed Cross

The operator must be able to select and display a fixed reference mark in the HUD and to position this reference anywhere on the vertical centerline of the display.

- 1 Set Quickener Gain to 1.0, constants A and $\Delta\tau$ to zero and constant b to 300.0

(This value for B is designed to increase the rate at which the tuning process converges).

- 2 Select the fixed reference in the display

- 3 Stabilize the aircraft at 400 knots and 1500 ft, move the fixed cross so that it overlays the CDM.

- 4 Increase the flight path angle by +5 deg, using the quickened CDM and pitch ladder. Note the movement of the aircraft symbol relative to the fixed cross.

- 5 If the CDM lags the fixed cross the time constant is too short and $\Delta\tau$ should be increased. Similarly, if the CDM leads the fixed cross $\Delta\tau$ should be decreased.

- 6 Repeat step 5 using flight path changes of +/-5 and +/-10 deg and a range of pitch rates. After each test allow at least 5 sec for the quickener to stabilize before making a further input. It is unlikely that all relative movement can be eliminated as a first order quickener is being used to match a higher order system having a predominant first order mode. The operator should, therefore, aim to obtain the best match for a range of inputs of varying magnitude and rate. If two values of $\Delta\tau$ give equally good matches then these alternatives should be evaluated with the quickener gain set to 0.7 and the value giving the best handling qualities should be selected. The aim, during the final iteration, should be for $\Delta\tau$ to be within +/- 0.01.

- 7 Record the values of true airspeed (v_{tr}), relative density ratio (σ_r) and $\Delta\tau$, appropriate to this test condition (400 knots/1500 ft). Provided v_{tr} and σ_r are recorded at the same point in time then small variations in speed and height during the test maneuvers are taken into account.

- 8 Reset $\Delta\tau$ to zero and repeat steps 2 through 7 for 250 knots and 1500 ft.

9 Record values of v_{11} , σ_1 , and $\Delta\tau_1$ for this second flight condition.

10 Compute new values for A and B using the following expressions:

$$\tau_1 = A_{old} + \frac{B_{old}}{[v_{11}\sigma_1]} + \Delta\tau_1$$

$$\tau_2 = A_{old} + \frac{B_{old}}{[v_{12}\sigma_2]} + \Delta\tau_2$$

$$A_{new} = \frac{[\tau_1 v_{11}\sigma_1 - \tau_2 v_{12}\sigma_2]}{[v_{11}\sigma_1 - v_{12}\sigma_2]}$$

$$B_{new} = [\tau_1 - \tau_2] \frac{[v_{11}\sigma_1 v_{12}\sigma_2]}{[v_{11}\sigma_1 - v_{12}\sigma_2]}$$

11 Reset $\Delta\tau$ to zero and repeat steps 3 through 10 with these new values of A and B until $\Delta\tau_1$ is less than ± 0.02 and $\Delta\tau_2$ is less than ± 0.01 (i.e., τ at the two flight test conditions is defined to an accuracy of around $\pm 1\%$).

12 Reset the quickener gain to 0.7 and evaluate the handling qualities of the vehicle at both the above test conditions.

13 Reset the quickener gain to 1.0. Check the operation of the quickener, by evaluating the relative movement between the CDM and the fixed reference at a sufficient number of alternative speeds, heights, aircraft configurations and aircraft masses to ensure that τ is adequately predicted over the full operational flight envelope and range of configurations and masses of the aircraft. Where there is doubt as to the match, then the handling qualities of the vehicle should be evaluated at that condition with the quickener gain set to 0.7.

As a minimum, the tuning of the quickener should be checked at:

- i) 3 speeds at 3 heights to cover the full range of these operating conditions

- ii) 3 aircraft masses at 1 or 2 critical operating conditions

There is no further opportunity to tune the quickener. Should a satisfactory match not be obtained at any operating condition then the simple form adopted for the variation of τ with flight condition and aircraft configuration would have to be re-appraised.

14 Reset the quickener gain to 0.7.

Note: The time constant τ used in the expression for Q_1 should be forced to a small value (e.g., 0.3sec) above 60 deg absolute theta in order to speed the recovery of the filter after thetadot has changed sign through the zenith and nadir.

6.1.2. Blending of Q_1 and Q_2

In order to avoid inconsistencies in the climb/dive ladder and the flight path marker as the climb/dive angle increases through the zenith and nadir, the quickener used to compensate the ladder and FPM (i.e., Q_1) must be blended into a pitch rate quickener (i.e., Q_2) at the higher climb/dive angles. The following terms, B_1 and B_2 , are used to blend Q_1 and Q_2 between low and high pitch angles.

$$B_2 = \begin{cases} 0 & |\theta| \leq 30^\circ \\ \frac{|\theta| - 30^\circ}{55^\circ - 30^\circ} & 30^\circ < |\theta| < 55^\circ \\ 1 & |\theta| \geq 55^\circ \end{cases}$$

$$B_1 = \begin{cases} 1 & |\theta| \leq 30^\circ \\ 1 - B_2 & 30^\circ < |\theta| < 55^\circ \\ 0 & |\theta| \geq 55^\circ \end{cases}$$

During normal flight:

$$FPMQ = CDLQ = Q_1 \times B_1 + Q_2 \times B_2$$

$$CDAMQ = Q_2$$

During ILS mode or landing gear down:

$$FPMQ = CDAMQ = CDLQ = Q_1 \times B_1 + Q_2 \times B_2$$

6.2. CAGING OF THE CDM

Caging is a means by which the lateral displacement of the FPM is restricted to reduce the adverse affects of large beta angle caused by excessive crosswinds or sideslip. The concept of the caged FPM (i.e., climb/dive marker) as the primary control reference is not a new idea as many current aircraft including F-16 and F-15 incorporate a similar feature called drift cutout. The benefit of the climb/dive marker (CDM) and drift cutout is that it stabilizes the primary flight symbology within the lateral axis of the HUD by removing the effect of beta (i.e., drift due to winds or sideslip).

The following set of equations position the FPM, CDM, and CDL. When positioning the FPM and CDM, a positive azimuth angle is to the right of the ARP and a positive elevation angle is above the ARP.

The FPM's position relative to the ARP is dependent on the aircraft's true velocity vector. The following equations located the FPM as an azimuth and elevation displacement, in degrees, from the ARP.

uA = Velocity X Body Axis (positive along aircraft axis)

yA = Velocity Y Body Axis (positive out right wing)

wA = Velocity Z Body Axis (positive down)

The following intermediate equation is used in positioning the CDM and CDL:

ϕ = Aircraft Roll Angle (positive right wing down)

$$VV_{el} = FPM_{el} * \cos \phi - FPM_{az} * \sin \phi$$

The CDM's position relative to the ARP is defined in the following equations:

α = Aircraft Angle Of Attack

$$CDAMAZ = 0.0$$

$$CDAMEL = VVEL \cos \phi - \alpha \sin^2 \phi + CDAMQ$$

The CDL is positioned relative to the CDM using the following equation:

θ = Aircraft Pitch Angle

$$CDLEL = VVEL + \theta + CDLQ$$

7. COMPRESSION

The spacing of the CDL bars is compressed from a 1:1 ratio to a 4.4:1 ratio. The horizon line and the 5 degree climb/dive bar are spaced at a 1:1 relationship with the outside world. The compression ratio then increases linearly to a 4.4:1 ratio at the 90 degree zenith/nadir symbol. The following are the general equation used to position the climb bars, dive bars, and zenith and nadir symbols.

The first step is to find the equation that transforms the input angle x , of domain $[5,90]$, to the proper compression ratio of the range $[1,4.4]$.

$$m = \frac{4.4 - 1.0}{90 - 5} = \frac{3.4}{85}$$

$$CompressionRatio = \frac{1}{m(x-5) + 1}$$

In order to find the distance from the horizon for the input angle x , we must add up all the compression ratios between the 5 degree bar and the input angle and add 5 for the distance from the horizon line to the 5 degree bar.

$$distance = \int [CompressionRatio] dx + 5.0$$

$$distance = \int \left[\frac{1}{m(x-5)+1} \right] dx + 5.0$$

$$distance = \frac{\ln[m(x-5)+1]}{m} + 5.0$$

APPENDIX B
Phase I Debrief Questionnaire

HUMAN FACTORS EVALUATION OF HUD SYMBOLOGY

Pilot ID # _____ Run # _____
Display used this trial: X Head Up Display Head Down Display

Instructions:

This questionnaire is designed to assess Human Factors concerns associated with the proposed HUD symbology. Please read all instructions carefully. Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each statement.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

1. I was able to rapidly determine what unusual attitude I was in as soon as I saw the HUD. _____

Comments: _____

2. At first glance at the HUD, I was able to determine which control inputs were required for recovery. _____

Comments: _____

3. As I performed the unusual attitude recovery, HUD indications were confusing. _____

Comments: _____

4. I was confident of my spatial orientation during the unusual attitude recovery. _____

Comments: _____

5. I was confident of my spatial orientation after the unusual attitude recovery. _____

Comments: _____

6. There was too much information presented on the HUD for an unusual attitude recovery. ____
 Comments: _____

7. The HUD was easier to use than the HDD when recovering from unusual attitudes. ____
 Comments: _____

8. This HUD is safe to use for unusual attitude recovery. ____
 Comments: _____

9. I would feel comfortable using this HUD as my primary flight reference for both instrument flying and unusual attitude recoveries. ____
 Comments: _____

The following statements apply to the ILS and Navigation tasks.

Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each statement.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

9. It was easy to perform instrument cross checks with the HUD. ____
 Comments: _____

10. The HUD was easier to use than the HDD when performing the ILS task? ____
 Comments: _____

11. The HUD was easier to use than the HDD when performing the NAV task? ____

Comments: _____

12. There was enough information presented on the HUD to accomplish the ILS task. ____

Comments: _____

13. There was enough information presented on the HUD to accomplish the NAV task. ____

Comments: _____

For the next four statements, rate each of the boldface items as they would be inserted in the sentence. Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each parameter or component.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

14. While using the HUD, I was able to adequately control the required ____.

Altitude _____
Airspeed _____
Bank angle _____
Heading _____
Flight Path Angle _____

Comments: _____

15. The _____ component of the symbology used in the HUD was easy to interpret.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

16. The _____ component of the HUD is placed where it is easy to cross check while performing the ILS task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

17. The _____ component of the HUD is placed where it is easy to cross check while performing the NAV task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

For the next two statements, rate each of the boldface indications as they would be inserted in the sentence using the following scale.

Not enough
1

Just right
2

Too much
3

18. While using the HUD, rate the resolution of the _____ while performing the ILS task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

19. While using the HUD, rate the resolution of the _____ while performing the NAV task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

The following statements apply to the Weapon Delivery mission.

Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each statement.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

21. I was able to successfully negotiate the low level portion of the mission using the CDAM and tadpole steering cue. _____

Comments: _____

22. The relationship of the FPM to the CDAM enabled me to readily determine an approximate direction and magnitude of the winds on the low level. _____

Comments: _____

23. Given sufficient training, I believe I would be able to successfully accomplish the bombing mission. _____

Comments: _____

24. Do you envision any conflicts between the HUD symbology, as presented, with any of the missions or mission symbology you are currently flying (YES/NO). If yes, please explain.

Comments: _____

We have tried to make this questionnaire as complete as possible however, if you feel we have not addressed an important issue or have any additional comments about the HUD symbology please let us know.

The three things I like the most about the HUD were:

1. _____
2. _____
3. _____

The three things I disliked most about the HUD were:

1. _____
2. _____
3. _____

Additional comments :

APPENDIX C

Phase I Pilot Questionnaire Responses

HEAD UP DISPLAY

1. I was able to rapidly determine what unusual attitude I was in as soon as I saw the HUD.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	2	12	5

- Subject 3: 5, At extreme pitch attitudes (especially nose up) I had trouble acquiring the ghost horizon and determining which way to roll.
- Subject 5: 5, Most of the time. Lower on nose low v-60 degree, wings level.
- Subject 6: 5, Nose low was very good. Nose hi was also good but not as easy as seeing "all white" on the ADI. Very nose Hi (80 degree +) was confusing at first because of the HUD spin.
- Subject 7: 4, HUD Symbology takes a moment to interpret in all attitudes.
- Subject 8: 4, Although this HUD is better than the present one, it still takes longer to determine the attitude vs head down
- Subject 9: 5, For the most part yes, occasionally I would get momentarily confused and make an incorrect initial move. I recognized my mistake immediately afterwards.
- Subject 11: 6, I liked all symbology except ghost horizon.
- Subject 15: 5, The more it was used, the easier it became to determine the attitude quickly.
- Subject 16: 5, Only a few times did I have to pause to confirm the UAR. This occurred in a nose-up situation with less than 30° of bank. The lost horizon was present, but not instantaneously usable.
- Subject 17: 5, Had to think more than on the ADI.
- Subject 20: 5, Once I practiced I keyed on a few things and never really saw the others. Each person maybe different. Decluttering those things that I don't use would help (like Nadir/Star/Nav info)
- Subject 21: 5, When the ghost horizon was at the bottom, I had to lift my head up to find it.

2. At first glance at the HUD I was able to determine which control inputs were required for recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	0	0	14	5

- Subject 3: 5, See #1 Once I began rolling the ghost horizon became obvious.
- Subject 5: 5, Same as 1
- Subject 6: 5, The only real hard part here was determining the A/S. The little "K" sucks. It clutters the dial.
- Subject 7: 5, Again exact attitude takes a while to interpret on the HUD so proper control input takes a moment to determine in all attitudes.
- Subject 8: 5, Pretty much so, there is still some interpretation to be done.
- Subject 9: 5, same as above

- Subject 14: 5 For both 1 & 2, I felt safe conducting unusual attitude, but thought it took me longer to analyze the presentation and make proper inputs than on the HDD. It maybe that I'm just not used to unusual attitude recovery on HUD.
- Subject 16: 5, See #1 above. When in an extreme pitch-down with NADIR slowing and wing level, I paused momentarily to confirm if I was short of or past the 90° point, even though in my thought process, it appeared obvious, I still wanted to confirm the right direction/move.
- Subject 18: 2, Sometimes confused as to inverted or upright.
- Subject 21: 6, Same as above.

3. As I performed the unusual attitude recovery, HUD indications were confusing.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	11	6	0	1	1	1

- Subject 3: 1, No problems noted once recovery was begun.
- Subject 5: 1, never
- Subject 6: 2, I don't like doing these on any HUD, period. If I had to this one works. The post recovery SA is higher on the HUD because of the CDAM
- Subject 8: 1, Once the recovery was underway the HUD was easy to follow.
- Subject 14: 1, never confusing, just took the brand name second to analyze
- Subject 15: 2, Only in a couple cases, mostly inverted.
- Subject 17: 5, The nonconstant rate of the pitch bars was deceiving.
- Subject 18: 1, Pitch ladder was good.
- Subject 23: 4, Medium energy (250-350kias) recoveries results in rapid recoveries = pitch ladder become a bit of a blur, as opposed to ADI

4. I was confident of my spatial orientation during the unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	4	17

- Subject 3: 6, Very easy and comfortable to use after beginning the recovery.
- Subject 5: 6, no problems
- Subject 7: 5, Roll orientation lags on the HUD and causes a roll-pio in some situations, also, if the wings on the CDAM were a little longer, you might have a better perception of roll rates.
- Subject 8: 6, Again, once interpreted the HUD is easy to read.
- Subject 23: 6, Once recovery was initiated, indications were very clear and straight forward related though to 3

5. I was confident of my spatial orientation after the unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	19

Subject 3: 6, Excellent. Easy to find level flight at all airspeeds/AOA.
 Subject 5: 6, no problems
 Subject 6: 6, see "3"
 Subject 7: 6, The CDAM makes it easy to establish and maintain level flight.
 Subject 8: 6, same as above
 Subject 18: 6, Easily interpreted.

6. There was too much information presented on the HUD for an unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	9	6	1	1	3	0

Subject 1: 2, It is fairly easy to focus on the most important information: CDAM/Pitch ladder and airspeed/altitude.
 Subject 3: 2, The display appeared cluttered at times but didn't overly detract from recovery.
 Subject 7: 5, Never used the bank indicator. Also, the Nav text takes up lots of room and doesn't help at all. The "dials" around the airspeed and altitude don't help since you have to read the airspeed anyway.
 Subject 11: 2, only ghost horizon
 Subject 12: 4, sky pointers are extra symbols not needed
 Subject 20: 5, There's a lot of stuff (info) in there one could never hope to read process, and use.
 Subject 21: 5, Don't need mag heading or during turn & slip indicator recovery.
 Subject 23: 2, In this test HUD, HUD tends to clutter at corners.

7. The HUD was easier to use than the HDD when recovering from unusual attitudes.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	2	1	8	6	1	2

Subject: 1: 4, Scored 4 only because a G meter was available in addition to tones to max perform recovery.
 Subject 3: 5, In most cases except very nose high with ghost horizon pegged at bottom of display..
 Subject 4: 3, Same comments as on HDD survey.
 Subject 5: 3, On high AOA NH recoveries, on roll-out. The symbology would sink very low in the HUD.

- Subject 6: 4, The initial "Look" (determining attitude) was not as good as the HDD, mainly due to mono-color display. The blk & white on the ADI works well.
- Subject 7: 1, Its always easier to recognize the unusual attitude head-down while it takes some interpretation head-up. Also, distance from the horizon (in pitch angle) is easier to perceive HD this allows you more time to keep cross checking alt and airspeed.
- Subject 8: 1, with HDD, the picture is "instantaneous" and its something I'm more familiar with.
- Subject 9: 3, No, I still find the ADI simpler to interpret than the HUD.
- Subject 11: 2, I feel the ADI is the easiest instrument to use for unusual At. recoveries.
- Subject 14: 3, I think this is just do to prior training for 1500 hrs of flying features I have been taught to recover off the ADI. Old habits are hard to break.
- Subject 15: 4, They actually were about the same.
- Subject 16: 3, This is a "push" (3 1/2). The HDD, because of color contrast take away the possible confusion of the HUD. Still, the HUD was very usable.
- Subject 18: 6, Bigger, easier crossover.
- Subject 20: 3, "Even" at ease of recovery.
- Subject 21: 4, Both were easy but I definitely like my head up during recoveries.
- Subject 22: 6, Good climb/dive on pitch info.
- Subject 23: 4, In extreme nose up/down with ADI, at or near vertical HDD is confusing while HUD is not with indexes pointing to horizon

8. This HUD is safe to use for unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	0	0	3	17

- Subject 3: 6, Always felt that I could complete a safe recovery.
- Subject 7: 2, If you know you are in an unusual attitude it takes longer HUD than HDD to determine the condition. I think that if just found your self in an unusual attitude that difference in time to figure it out would be increased. Also, around the horizon the difference between nose high and nose low are small. If you were expecting to see slightly nose high right turn and you were really 180 degrees out from that I'm not sure you would recognize it. The two colors of an ADI make that type situation immediately apparent. Maybe making the pitch bars have a more noticeable bend to them even around the horizon would help. One in a recovery it is executable on the HUD, but since the field of regard is small you tend to fixate on pitch and don't check other instruments as much as HDD. The HUD is very good for establishing level flight past recovery. That's nice, but if I was really doing an unusual attitude recovery, the precision isn't necessary (a little up would be good for me) The CDM does provide this data much quicker than HD instruments so its defiantly a good thing. I would not recommend doing recoveries on the HUD, HDD's are much better except for establishing precise level flight and quicker confirmation of stopping a sink rate. Recover HD then check the CDM and game would be my technique
- Subject 8: 5, It's safe, but not as safe as HDD.
- Subject 9: 6, yes it is safe.
- Subject 11: 6, All information is easily read.

Subject 16: 6, With the current display, tapering, gearing, etc., training is the key to the success and safety of its use. Practice will lead to confidence in the display.

Subject 23: 6, It with proper assurances, training, attitude reliability etc.

9. It was easy to perform instrument cross checks with the HUD.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	2	4	14

Subject 1: 6

Subject 2: 5

Subject 3: 6, All info was in a predictable place and a rapid cross check was easy to do.

Subject 4: 6

Subject 5: 6

Subject 6: 5, The "K" on the A/S dial sucks, it cluttered the display.

Subject 7: 6

Subject 8: 6

Subject 9: 6, Workload was greatly decreased as everything was right in front of me.

Subject 11: 6, All information is easily read.

Subject 12: 6

Subject 14: 6, very nice!

Subject 15: 6, No comment.

Subject 16: 4, Instantaneous field of view caused a certain amount of less movement; not required with HDD.

Subject 17: 5, No comment.

Subject 18: 6, Easier crosscheck because all in one localized area.

Subject 20: 5, The airspeed indicator is difficult to use..Perhaps because its difference from the real airspeed gauge. It takes a second to process what happened for me was that I solely read the digital read out.

Subject 21: 6, No comment.

Subject 22: 6, No comment.

Subject 23: 4, Take "K" out of IAS indicator. Perhaps test HUD is the problem at IAS/Altitude too far apart, seems like Head down. I can crosscheck with better cognizance, less work, then again 26 seconds of inst. flying, 13 with HUD, would make it so.

10. The HUD was easier to use than the HDD when performing the ILS task?

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	1	2	3	14

Subject 1: 5, Once the sensitivity of the HUD is understood, it is easier to fly a more accurate ILS.

Subject 3: 6, Very easy to do a precise ILS.

Subject 4: 6, Excellent precise guidance.

Subject 5: 5, It's a higher workload because your deviations look larger. But the level flight picture didn't change w/AOA.

- Subject 7: 6, Small ADI and stop gauge made HDD INS particularly difficult. However, even with a bigger ADI and round dials the HUD would still be better for precision Instruments than HDD, the difference wouldn't be so great.
- Subject 8: 6, Easier cross check, much better and more accurate climb/dive information.
- Subject 9: 6, Fewer head movements made it easier.
- Subject 12: 6, cross check time slowed way down.
- Subject 14: 6, you could fly a very precise ILS with info present.
- Subject 15: 6, Crosscheck seemed to be quicker, resulting in better performance.
- Subject 16: 3, HUD display shift based on AOA/airspeed does not occur on the HDD. HUD display shifted down at slow airspeed/high AOA, which could lead to disorientation.
- Subject 18: 6, The HUD was an excellent pitch ladder and airspeed and altitude indicators. Heading grad_____ could be more refined for precision approaches (PARs). AOA indicator needs a caret or similar item that stays abeam the velocity vector rather than the E bar moving around. Will facilitate an easier crosscheck. Localizer and glideslope are good.
- Subject 20: 6, Flight path indicator makes it easier.
- Subject 21: 4, Occasionally, I would miss the capture of the pitch AAR because it was too low. I also use VVI during an ILS which wasn't available.
- Subject 23: 6, ILS on HUD resulted in tighter parameters for same type of small horizontal/course deviations. I like AOA indicator to be reversed.

11. The HUD was easier to use than the HDD when performing the NAV task?

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	1	1	4	13

- Subject 1: 6, Much easier to use primarily because of CDM. No VVI instrument delay for level offn and turns when changing airspeed.
- Subject 3: 6, Would like some form of VVI to calculate level-off lead altitude.
- Subject 4: Need to be able to set heading and A/S to perform this task as written ie. this was a "memory" nav task.
- Subject 5: 5, same as above.
- Subject 6: 5, General SA was better in the HUD but: (1) The "K" on the A/S sucks. (2) the lack of "Capt Bars" to mark headings would help the HUD alot. (3) the CDM help alot.
- Subject 7: 6, (Same comments as 10) also, heading on the HUD is easier because of the expanded scale. All instruments are conveniently located so close you can easily cross check them and be very precise.
- Subject 8: 6, same as above
- Subject 11: 6, You could be very precise with the HUD.
- Subject 15: 6, Crosscheck seemed to be quicker, resulting in better performance.
- Subject 16: 3, I felt my performance was better on the HDD than the HUD, which could have been due to the sensitivity perceived lookin at the CD marker and CD ladder versus the ADI. 5° on the ADI is different than 5° on the HUD in relation to the visual perception. HUD appears more sensitive
- Subject 17: 6, See Question 11.
- Subject 21: 6, I like the CDM always giving you level information even at high AOA/slow speed.
- Subject 22: 5, A/S and ALD to small.

Subject 23: 5, Relating to provide comments, HUD Bank/HDG and A/S - Alt could be grouped tighter or my cross check could use some work.

12. There was enough information presented on the HUD to accomplish the ILS task.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	6	14

- Subject 1: 5, When south of the localizing course heading NW, you need a bearing pointer somewhere in the cockpit to tell you how close to course you are (3 radials vs 20 radials)
- Subject 3: 6, The AS and ALT markers are great! I don't like the AOA bracket it isn't intuitive would prefer something that is more like the round dial type.
- Subject 5: 5, Need some control instrument for A/S RPM/ITT/Fuel flow in digital readout might work.
- Subject 6: 5, I missed having bearing pointer info for the intercept.
- Subject 8: 6, But ...the AOA needs more emphasis. This HUD bases approaches on airspeed should use AOA
- Subject 12: 5, I would like to know where I'm at in relation to the station (situational awareness)
- Subject 14: 6, I still think a VVI presentation might be worthwhile, especially for PAR's& Non-precision.
- Subject 16: 6, Instantaneous field of view caused/necessitated some head movement or seat adjustment. Not necessary with head-down instruments.
- Subject 18: 6, See Question 11.
- Subject 21: 5, need VVI.

13. There was enough information presented on the HUD to accomplish the NAV task.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	1	0	4	15

- Subject 3: 6, Only problem noted was at very slow speeds all infor (FP marker CDM, bank scale) get compressed at the bottom of the display.
- Subject 4: 3, see comments from #11 above
- Subject 5: 5, same as above.
- Subject 6: 5, Need "Capt Bars"
- Subject 7: 5, A heading marker would be nice to have
- Subject 16: 6, See #12.
- Subject 18: 6, See Question 11.

14. While using the HUD, I was able to adequately control the required.

- Subject 1: Digital alt & airspeed much easier to be more accurate with but never even saw VVI indications in HUD.
- Subject 3: No direct readout of VVI have to calculate (VVI was never specified in any task).

- Subject 5: Need control inst for airspeed.
- Subject 6: (1) The "K" on the A/S dial sucks. (2) the heading display is inadequate for PARs
- Subject 7: Excellent control of angle but no actual vertical velocity readout (not necessary)
- Subject 8: Airspeed (5) Get rid of the "K" on the A/S indicator. Vert. Vel (4) indirectly using CDAM I never used the VVI readout.
- Subject 14: No VVI (but most tasks on this test did not require VVI air climbs & dives were directed as 3 degrees at a particular A/S.
- Subject 15: Vertical velocity was not presented, but it was easy to control pitch attitude.
- Subject 16: VVI to maintain "0" is very workload intensive (you try to maintain "0"). Need a dampened VVI like HDD.
- Subject 18: Digital readout of alt/airspeed should be larger; heading scale should be in 2° increments, not 5°.
- Subject 21: Occasionally would lose band & heading info out of view. No VVI info.
- Subject 22: A/S & ALT both took longer to interpret them with a trip gauge heading - in the F-16 we can read exact heading (030) is in a box VVI not in this HUD.

15. The _____ component of the symbology used in the HUD was easy to interpret.

Comments:

- Subject 2: K in A/S symbology should not be in the circle either outside or not at all.
- Subject 3: Glide Scope - LOC/CDI ** When intercepting GS the pitch director instantly indicates your above GS, this needs to come down from top of display for a smooth intercept. Pitch Ladder - Pitch ladder is easy to intercept but numbers are blurred at high pitch rates during recoveries (most notably during nose high recoveries while pulling to the horizon.)
- Subject 4: The AOA was unusable and cluttered the HUD. Move it to the side and give me numbers.
- Subject 5: Glideslope - 6, didn't see it until it was pointed out to me again, then it was easy.
- Subject 6: Airspeed - The "K" sucks, clutters the display.
- Subject 7: Pitch ladder -(5) accentuate the difference around the horizon.
Bank Scale - (5) the expanding bank scale just got in the way, if I'm at 90 degrees at bank I don't care if I'm at 85 degrees or 90. Scale is nice otherwise for precision instruments not needed except for flying approach.
LOC/CDI - (5) When you have a cross wind because the CDI has such a large gap in it, it is hard to tell if you are exactly on course.
Airspeed/Altitude - (6) easy to interpret but extra symbology. You have to read the digital airspeed and altitude anyway (or you wouldn't know the hundreds digit) the round gauges just take up extra space and clutter the HUD. It would be nice to have the altitude "gauge" appear in the last 500 of a decent and then have DH caret available, but other than that its just extra symbology making it harder to read the important information.
- Subject 8: AOA (2) The AOA readout should be more prominent. VVI (1) the VVI never come into play.
- Subject 14: Pitch ladder is better than previous ones AOA presentation was kind of non-factor.
- Subject 16: Similar to #14, number easy to read "6." Easy to use "4." Frustration inducing "6."
- Subject 17: Glideslope and LOC/CDI get in the way of the steering bars and need to be more pronounced.

- Subject 21: I was getting use to the AOA info but still found it hard to interpret quickly. VVI doesn't exist. I missed glideslope flight director info initially on occasion.
- Subject 22: AOA reverse of what I use in the F-16. VVI not in the HUD AS/ALT too small.

16. The _____ component of the HUD is placed where it is easy to cross check while performing the ILS task.

- Subject 3: AOA bracket tends to clutter center of display and intuitively moving CDM to fix AOA detracts from maintaining GS.
- Subject 4: Didn't need VVI for ILS. AOA gets lost in with CDI.
- Subject 6: The LOC/CDI RAW Data is cluttered with other info on glideslope. Need to move DME etc. somewhere else when gear is down.
- Subject 11: HUD was very easy to use for instrument flying.
- Subject 16: Bank scale and heading (even though not part of the question are slightly out of the IFOV. Need to move head to use. Again, seat height is critical.
- Subject 18: AOA and VVI--discussed previously.
- Subject 21: I like the 3 degree down cue.
- Subject 22: AOA/ALT/AS placed well but not the easiest to interpret, VVI not present.
- Subject 23: Bank Scale -too low, A/S, Altitude closer together

17. The _____ component of the HUD is placed where it is easy to cross check while performing the NAV task.

Comments:

- Subject 3: CDM gets too low at low A/S
- Subject 6: The addition of "Capt Bars" type of gizmo would help a lot.
- Subject 7: Put heading marker on the HUD
- Subject 11: same as above
- Subject 16: Heading should be included here. "3." See #16.
- Subject 18: If you have to focus your eyes to an AOA scale that is shifting up or down, you will tend to pull or push the aircraft nose to it when a power adjustment is normally the required input.

18. While using the HUD rate the resolution of the _____ while performing the ILS task.

Comments:

- Subject 3: LOC is a little sensitive especially during initial intercept.
- Subject 6: Flt Dir needs to be wider or something. They don't stand out enough.
- Subject 7: Airspeed/Altitude cluttered by extra symbology hard to read numbers. LOC very thin could be a slightly smaller gap.
- Subject 11: Very easy to fly instruments with this HUD
- Subject 14: Resolution great!
- Subject 16: Heading should be included here. "3." See #16.
- Subject 18: Good.
- Subject 22: AS & ALT had to be read out not just glanced at, VVI not available.
- Subject 23: Bank/nav could be a little bigger. A/S/Alt make cardinal lines longer.

19. While using the HUD rate the resolution of the _____ while performing the NAV task.

Comments:

- Subject 6: Get rid of the "K". Too cluttered.
Subject 11: Same as above
Subject 14: Great!
Subject 18: You left out heading! Need better refinement capability of pilot + or - 2° not 5°. Splitting the difference may be good enough usually, but not when the ceiling is 100 ft in 1/4 mile vis.
Subject 22: Alt & A/S same as above.
Subject 23: see above

20. The three things I like the most about the HUD were:

- Subject 1: (1) Don't have to move eyes very far to see all necessary data to fly instrument
(2) CDM much more accurate than ADI especially during A/S chg.
Subject 2: Pitch ladder symbology. (2) CDM - easy to fix VVI
Subject 3: Very easy to fly precise instruments. A/S and Alt makers are excellent. Ghost horizon is very helpful.
Subject 4: Different pitch ladder for up vs down. Round dial A/S and ACT. Bank angle presentation.
Subject 5: LVL is always LVL. Fly down the funnel.
Subject 6: CDM, Pitch ladders
Subject 7: Concentrated presentation of information makes for easy cross check. Centering steering in the circle of the CDM makes flying an ILS easy. Digital airspeed and altitude.
Subject 8: The stabilized climb/dive marker. The "funnel & bucket" pitch ladder. The bank scale.
Subject 9: Pertinent information displayed in one place. Easier to perform crosscheck. Expanded pitch scale made precision flying easier. Liked the round dial/digital display for A/S & Alt.
Subject 11: It made instrument flying easy. Round dials for airspeed, alt - excellent.
Subject 12: Concise information. Easily readable.
Subject 14: Difference between upper & lower Pitch Ladders. Raw data for ILS. Airspeed & Altitude Presentation.
Subject 15: Easy crosscheck; appropriate information presented; good pitch, ladder scaling, and presentation.
Subject 17: The airspeed and altitude displays; the horizon line.
Subject 18: Pitch ladder; airspeed/altimeter; format (display layout).
Subject 20: Pitch ladder, heading display, alt. display.
Subject 21: The CDM. Ghost horizon, and easy to interpret.
Subject 22: Pitch ladder for climb/dive, CDI presentation.
Subject 23: Horizon ghost in unusual attitudes recoveries. A/S/Alt indicators with digital readouts. Bank indicator.

21. The three things I disliked most about the HUD were:

- Subject 2: CDI/LOC steering bar interference hard to interpret when overlapping. Recommend a single cue for ILS ft director. Hdg reference mark occluded by CDI pointer arrow on ILS dogleg.
Subject 3: AOA bracket is not intuitive and clutters display. As seen here in SM; flashing and wavy lines distracting. At low speed becomes cluttered at bottom of HUD.

- Subject 4: AOA. Inability to mark heading and A/S during Nav task. I had to lean forward to see entire presentation.
- Subject 5: No airspeed "Control" intr (just performance). Symbols would sink to bottom of FOV @ High AOA
- Subject 6: The lack of bearing info for approaches. (2) No "Capt Bars" to mark headings. (3) The "K" on the airspeed indicators.
- Subject 7: Difficult to immediately determine unusual attitude compared to HDD. Needs to be more difference in the horizon. Extra symbology see below. Lack of a heading marker.
- Subject : AOA display on ILS approaches. VVI readout. "K" on the airspeed indicator.
- Subject 9: Unnecessary "K" in airspeed dial.
- Subject 11: At slow airspeeds during unusual att. recov. HUD would become jumpy and confusing. Did not like ghost horizon. Did not like "K" on airspeed dial.
- Subject 12: Pitch ladder number on different sides, I would rather have them on one side with a negative sign for nose down plus being dashed lines would suffice "sky pointers, tabs, curve lines are not seen. Increase size of dashes so they can be seen.
- Subject 14: No VVI.
- Subject 15: Lack of VVI information.
- Subject 17: The unequal intervals of the pitch bars; the raw ILS data needs to be more prominent; no gun cross +. (Put this in a real jet (non F-16).
- Subject 18: ADA gauge (see previous comments/suggestions); heading scale (not enough gradient); size of digital display in airspeed/alt. Very usable HUD. However, only significant advancement (or enhancement) over F-15E HUD is trend data available in airspeed/and altimeter and the funnel/bucket pitchladder idea (good for crosscheck/unusual attitudes.
- Subject 20: Clutter with nav info. Airspeed indicator, high bank flight path indication for level flight.
- Subject 21: Lack of VVI for ILS. AOA information needs to be presented differently. Limited field of view.
- Subject 22: Altitude, Airspeed, AOA. Suggestion: Place the Heading in exact degrees in its own box, use tape gauges for airspeed and altitude.
- Subject 23: AOA direction of travel should be reversed to provide additional manning to pilot, as display hits sour test. Displaces size of entire display, pitch lines could be narrower, drowning display together. No heading set in HUD. Put data blocks in lower corners up and this will be easier to reference.

Additional Comments:

- Subject 2: Recommended setting up the unusual attitudes by looking somewhere else in the cockpit prior to recovery instead of closing eyes- this would be more realistic in actual instrument unusual attitude recoveries.
- Subject 3: Can barely see all of the display at one time especially top and bottom which sometimes precluded acquiring ghost horizon during UAR. Overall, HUD is superior to HDD for precise instrument tasks and is at least as good (and at times superior to) HDD for unusual attitude recoveries as tested.
- Subject 4: I would like a copy of MAT Foster Bitton's slides (used during training).
- Subject 6: Unusual attitude recoveries will never be as safe as the ADI. The "K" in the Airspeed indicator made it very difficult to see changes in A/S, it was too cluttered. The Raw data for ILS Glideslope ended up cluttered among the DME, NAVAID, info something needs to move. Didn't find the "Dashed Horizon" line that helpful. It wasn't a problem....just didn't help much. I

think most things on the HUD will work ok for IMC. I also think replacing the HDD with HUD only will kill people.

Subject 7: Round gauges around airspeed and altitude (see 15) Ground speed and mach number were not needed when flying instruments or should be selectable if desired. The block of text on the lower right is almost useless. The DME is good but unless the rest of the info is not displayed somewhere else in the cockpit its just clutter. The problem I had here is that the raw data glide path information (very important) gets lost in this block of non-critical information. The K on the airspeed is unnecessary it just clutters the display, its easy to remember airspeed on the left alt on the right.

Subject 8: I believe a colorized HUD would be easier to read/interpret.

Subject 12: I don't like CDM & FPM, not needed, just make the CDM act like AFPM in most airplanes, because it acts like a FPM in the vertical but not the horizontal anyway. For a guy flying low levels he would like to know for sure he can get through a valleyetc.

Subject 14: I liked the HUD alot! We've always known you can fly more precise instruments & nav off HUD. Now I believe you can safely recover unusual attitudes on HUD. The problem in the past; there's been no way to tell if the HUD or inputs into the HUD have failed and the HUD is inaccurate.

APPENDIX D

SWORD Data Collection Sheets

EXAMPLE SHEET

>>>> >>> >> > > EQUAL < << <<< <<<<

EXAMPLE 1 - Tasks X and Y are EQUAL in Workload

X ----- *

Y -----

EXAMPLE 2 - Task Y causes a little more Workload.

X ----- *

Y ----- *

EXAMPLE 3 - Task Y causes a lot more Workload.

X ----- *

Y ----- *

EXAMPLE 4 - Task X causes somewhat more Workload.

X ----- *

Y -----

Highest Workload for Head-Up/Head-Down Displays

	>>>>	>>>	>>	>	EQUAL	<	<<	<<<	<<<<	
HUD-UAR	—	—	—	—	—	—	—	—	—	HDD-UAR
HUD-UAR	—	—	—	—	—	—	—	—	—	HUD-ILS
HUD-UAR	—	—	—	—	—	—	—	—	—	HDD-ILS
HUD-UAR	—	—	—	—	—	—	—	—	—	HUD-PICT
HUD-UAR	—	—	—	—	—	—	—	—	—	HDD-PICT
HDD-UAR	—	—	—	—	—	—	—	—	—	HUD-ILS
HDD-UAR	—	—	—	—	—	—	—	—	—	HDD-ILS
HDD-UAR	—	—	—	—	—	—	—	—	—	HUD-PICT
HDD-UAR	—	—	—	—	—	—	—	—	—	HDD-PICT
HUD-ILS	—	—	—	—	—	—	—	—	—	HDD-ILS
HUD-ILS	—	—	—	—	—	—	—	—	—	HUD-PICT
HUD-ILS	—	—	—	—	—	—	—	—	—	HDD-PICT

Highest Workload for Head-Up/Head-Down Displays

	>>>>	>>>	>>	>	EQUAL	<	<<	<<<	<<<<
HDD-ILS	---	---	---	---	---	---	---	---	---
HDD-ILS	---	---	---	---	---	---	---	---	---
HUD-PICT	---	---	---	---	---	---	---	---	---

APPENDIX E
Phase II Debrief Questionnaires

HUMAN FACTORS EVALUATION OF HUD SYMBOLOGY

Pilot ID # _____ Run # _____
Display used this trial: X Head Up Display Head Down Display

Instructions:

This questionnaire is designed to assess Human Factors concerns associated with the proposed HUD symbology. Please read all instructions carefully. Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each statement.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

1. I was able to rapidly determine what unusual attitude I was in as soon as I saw the HUD. _____

Comments: _____

2. At first glance at the HUD, I was able to determine which control inputs were required for recovery. _____

Comments: _____

3. As I performed the unusual attitude recovery, HUD indications were confusing. _____

Comments: _____

4. I was confident of my spatial orientation during the unusual attitude recovery. _____

Comments: _____

5. I was confident of my spatial orientation after the unusual attitude recovery. _____

Comments: _____

6. There was too much information presented on the HUD for an unusual attitude recovery. ____
 Comments: _____
7. The HUD was easier to use than the HDD when recovering from unusual attitudes. ____
 Comments: _____
8. This HUD is safe to use for unusual attitude recovery. ____
 Comments: _____
9. I would feel comfortable using this HUD as my primary flight reference for both instrument flying and unusual attitude recoveries. ____
 Comments: _____

The following statements apply to the ILS and Navigation tasks.

Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each statement.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

9. It was easy to perform instrument cross checks with the HUD. ____
 Comments: _____
10. The HUD was easier to use than the HDD when performing the ILS task? ____
 Comments: _____

11. The HUD was easier to use than the HDD when performing the NAV task? ____

Comments: _____

12. There was enough information presented on the HUD to accomplish the ILS task. ____

Comments: _____

13. There was enough information presented on the HUD to accomplish the NAV task. ____

Comments: _____

For the next four statements, rate each of the boldface items as they would be inserted in the sentence. Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each parameter or component.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

14. While using the HUD, I was able to adequately control the required ____.

Altitude _____
Airspeed _____
Bank angle _____
Heading _____
Flight Path Angle _____

Comments: _____

15. The _____ component of the symbology used in the HUD was easy to interpret.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

16. The _____ component of the HUD is placed where it is easy to cross check while performing the ILS task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

17. The _____ component of the HUD is placed where it is easy to cross check while performing the NAV task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

For the next two statements, rate each of the boldface indications as they would be inserted in the sentence using the following scale.

Not enough
1

Just right
2

Too much
3

18. While using the HUD, rate the resolution of the _____ while performing the ILS task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

19. While using the HUD, rate the resolution of the _____ while performing the NAV task.

Pitch Ladder _____
Bank Scale _____
AOA _____
Flight Path Angle _____
Airspeed _____
Altitude _____
Glideslope _____
LOC/CDI _____

Comments: _____

The following statements apply to the Weapon Delivery mission.

Use the following scale to rate each statement. Write the number corresponding to your rating on the line after each statement.

Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
1	2	3	4	5	6

21. I was able to successfully negotiate the low level portion of the mission using the CDM and tadpole steering cue. _____

Comments: _____

22. The relationship of the FPM to the CDM enabled me to readily determine an approximate direction and magnitude of the winds on the low level. _____

Comments: _____

23. Given sufficient training, I believe I would be able to successfully accomplish the bombing mission. _____

Comments: _____

24. Do you envision any conflicts between the HUD symbology, as presented, with any of the missions or mission symbology you are currently flying (YES/NO). If yes, please explain.

Comments: _____

We have tried to make this questionnaire as complete as possible however, if you feel we have not addressed an important issue or have any additional comments about the HUD symbology please let us know.

The three things I like the most about the HUD were:

1. _____
2. _____
3. _____

The three things I disliked most about the HUD were:

1. _____
2. _____
3. _____

Additional comments :

APPENDIX F
Phase II Pilot Questionnaire Responses

HEAD UP DISPLAY

1. I was able to rapidly determine what unusual attitude I was in as soon as I saw the HUD.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	1	3	8	2

- Subject 1: 5, The HUD's asymmetric display aids to determine the unusual attitude, but there is a slight time delay in determining the actual unusual attitude.
- Subject 2: 6, For instrument flight, a VVI indication would be useful on the HUD.
- Subject 3: 5, Sometimes the symbology wasn't clear enough and not enough cues were immediately seen.
- Subject 4: 5, None-hi (climb) references were occasionally confusing. This was mainly because of prior experience/habit patterns.
- Subject 5: 5, I always knew which way to roll except when ghost horizon was not in view on a few occasions. Without teepes I had to use dashed or solid line pitch information to tell up or down.
- Subject 7: 5, In general yes. For some nose up recoveries, I need to use ghost horizon to determine correct inputs.
- Subject 8: 5, Nose low attitudes seemed easier to assess. I think this was due to the dashed lines and the unique funnel shapes.
- Subject 9: 2, Nose low was easy! But, nose high was more difficult because there seems to be fewer cues. I had to remember "numbers on left" during nose high UARs.
- Subject 10: 5, Dashed/solid lines are not as quickly recognizable as black/grey on ADI
- Subject 12: 4, Mostly after I had trained on the simulator the HUD display was obvious. However, I always had to think about the display before the unusual attitude. For the first couple of unusual attitudes per session, I made errors.
- Subject 13: 3, First attempt nose low I usually thought I was upside down, if I rehearsed display in my head before each run I could do OK. Nose high was hard to interpret.
- Subject 14: 5, Better than eagle HUD for UARs
- Subject 15: 4, Determining the attitude was not immediate. Finding and rolling to the horizon was easy.

2. At first glance at the HUD I was able to determine which control inputs were required for recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	2	2	6	5

- Subject 1: 5, Slight delay in recovering due to a slight unsureness of the unusual attitude.
- Subject 4: 5, Dive, no problem. Climb, see #1 above.
- Subject 5: 5, Same as above
- Subject 7: 5, In general, yes. See #1
- Subject 8: 6, By focusing primarily on the ghost horizon I found the UARs much easier head-up than head-down.
- Subject 9: 5, It took longer for me to analyze nose high UARs because of limited cues.

- Subject 12: 4, Control inputs come from what unusual attitude you think you are in.
 Subject 13: 3, Same as #1
 Subject 14: 6, Horizon line is great
 Subject 15: 4, After locating the horizon line, rolling/pitch were easy. Airspeed and altitude required some effort.

3. As I performed the unusual attitude recovery, HUD indications were confusing.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	10	4	0	1	0	0

- Subject 3: 2, A few times, the symbology was distorted enough to cause wrong direction inputs - possibly a sim problem.
 Subject 4: 2, Dive angle compression scales caused a little confusion. The changes in the scales without any physical inputs (g on body) causes a little confusion during the pulls back to the horizon.
 Subject 8: 1, Once I was able to confirm my attitude, the HUD indications were just what I expected.
 Subject 10: 1, Recovery was easy after up/down was determined
 Subject 12: 1, Once situational awareness was established in the unusual attitude, the recovery did not affect situational awareness.
 Subject 13: 2, Had some problems when passing 30 deg nose low due to change in "flow rate" of pitch ladder. Also had problems when I saw nose low (or high) pitch ladder lines above and below horizon simultaneously.
 Subject 15: 2, After several seconds (3) determining up from down is difficult.

4. I was confident of my spatial orientation during the unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	0	0	2	12

- Subject 4: 6, Never a problem of which way was up, but occasionally about how far up
 Subject 8: 6, No problems. Initial recognition was the most difficult aspect.
 Subject 12: 6, See #3
 Subject 13: 5, See #3
 Subject 15: 2, A bigger difference between the upper and lower lines is required.

5. I was confident of my spatial orientation after the unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	14

- Subject 4: 6, No problem

Subject 12: 6, Sec #3

Subject 13: 6, No problems once within 10 deg of level

6. There was too much information presented on the HUD for an unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	7	3	2	2	1	0

Subject 4: 4, Depending on orientation, occasionally there was too much information in line with the pitch ladders. (90deg bank)

Subject 5: 4, Didn't need VVI information or bank information

Subject 7: 5, Bank scale was pure clutter for nose low unusual attitude recoveries. Heading scale gets confused with straight pitch lines nose up.

Subject 8: 1, At times I thought the nadir and apex cluttered the HUD but they were also valuable by informing me of an extreme nose high or nose low attitude.

Subject 9: 1, Need better nose high cues. Nose low was outstanding with the _ _ _ / \ _ _ _ symbology. You knew instantly which way was up.

Subject 12: 1, Information displayed was not overwhelming

Subject 13: 3, Doesn't really give me compelling information as to my global position (up or down)

7. The HUD was easier to use than the HDD when recovering from unusual attitudes.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	4	5	2	1	1

Subject 2: 4, Because of the extensive head down training in the USAF, head down is still more comfortable.

Subject 3: 2, Easier to see at first glance on the HDD what is up or down

Subject 4: 4, The cross check was easier

Subject 5: 3, About the same

Subject 8: 5, Early on I thought the HUD was fairly difficult, but once you get used to the symbology it becomes slightly easier than head-down.

Subject 9: 3, A lot of good information is on the HUD, but the HUD is still much more obvious which way is up/down.

Subject 12: 1, The HUD is still not intuitive. The HUD was designed as a precise attitude reference and not a total attitude reference. As such, I don't think the HUD should be used for unusual attitude recoveries.

Subject 13: 2, Taken a lot of brain power to do interpretation

Subject 14: 3-4, HUD - Quicker response by merely pulling to horizon. HDD - Quicker assessment of overall position (quicker = easier)

Subject 15: 3, High pitch angles were easier/low pitch angles +/- 30 deg were easier heads down

8. This HUD is safe to use for unusual attitude recovery.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	1	1	0	6	6

- Subject 2: 6, With continued training in the system.
 Subject 3: 5, Requires practice regularly, though, to be able to rapidly respond to the "sight" picture.
 Subject 4: 5, Dive angle compression could give a false sense of security during a pullout/or cause confusion
 Subject 8: 6, I would have no problems trusting this HUD in a real UAR.
 Subject 12: 1, Not until a more intuitive display is developed. I think as a minimum, the HUD needs two different colors.
 Subject 13: 2, I don't think it's intuitive, especially nose high.
 Subject 14: 5, Except for when HUD is inoperative

9. I would feel comfortable using this HUD as my primary flight reference for both instrument flying and unusual attitude recoveries.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	1	0	1	5	6

- Subject 3: 5, Still prefer to glance at the HDD to crosscheck and verify (old habits will never die)
 Subject 4: 5, After more practice in a real jet and I felt confident it was working
 Subject 8: 6, Very easy to use
 Subject 9: 5, I would like to see a better (more obvious) symbology for pitch (nose high) and the CDM movement was sometimes confusing.
 Subject 12: 1, I would feel completely comfortable using the HUD for instrument flying, but not for unusual attitude recoveries.
 Subject 13: 2, No for unusual attitudes
 Subject 15: 4, But I would require the ADI.

10. It was easy to perform instrument cross checks with the HUD.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	2	12

- Subject 1: 4, Perfect seating height - some of the HUD items are near the edge of the instantaneous field of view.
 Subject 2: 6, An excellent display. One Problem, the bank indicator may get too close to the glide path and course indicators making it cluttered.
 Subject 3: 5, No comment
 Subject 4: 6, I don't like the dials around the airspeed and altimeter readouts

Subject 5: 6, Easier to be precise with flight path information. Grouping and location much better than HDD.

Subject 8: 6, Very easy

Subject 9: 6, Nice having all information closely grouped like that.

Subject 12: 6, Everything's there in a 15 deg by 15 deg field of view.

Subject 13: 6, Very easy to be precise

Subject 15: 5, Very precise

11. The HUD was easier to use than the HDD when performing the ILS task?

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	4	10

Subject 4: 4, Easier to pick up trend information, probably because of the size of the HDD instruments. Also it corrected for AOA automatically

Subject 5: 6, Same as #10

Subject 8: 6, Much easier to be precise

Subject 9: 6, Cross check was easier

Subject 12: 5, HUD ILS display is overwhelming.

Subject 14: 5, Flying the ILS on this HDD was a nightmare compared to F-15 HDD. Pitch and steering bars are much more sensitive on F-15 HDD, making it easier to stay on course and glidepath. If you're using the same deflection schedule head-down as head-up, I think you're doing head-down a disservice and skewing your data. It's not that hard to fly a head-down ILS!

Subject 15: 5, At slower speeds the bank steering indicator gets in the way

12. The HUD was easier to use than the HDD when performing the NAV task?

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	1	13

Subject 4: 5, Holding level flight was easy, but altitude level off lead points were indeterminable.

Subject 8: 6, The CDM and airspeed indicator make the most difference. I found the altimeter slightly difficult to use.

Subject 12: 6, No comparison

Subject 15: 6, But the F-16 has *%#& instruments (placement and size)! The F-15 may be a different story.

13. There was enough information presented on the HUD to accomplish the ILS task.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	1	0	0	2	11

Subject 4: 5, Sometimes too much. The pitch bar blended in with other information.

Subject 5: 6, Need VVI information

Subject 7: 6, Too much, get rid of the 3 deg line. It's useless clutter.

Subject 8: 6, Yes, I really liked the AOA/power indicator

Subject 9: 2, When established on course/glidepath, the bank director directly overlays the CDI and I would still like an indication of the course unobstructed by the flight director. The glide slope indicator is just fine.

Subject 12: 1, Too much information! The display was way too cluttered. The 3 deg nose down line should be removed, the energy management cue removed, the flight director made to a single cue, the bank pointer moved to the bottom of the scope as a start. Erase all of the TACAN and ILS channel information. The ILS display worked OK once you were set and established on final. However, once significantly off course, the ILS display was very confusing with all the overlapping information. Make it simple!

Subject 13: 6, The 3 deg pitch ladder is in the way! The information is all there, just cluttered.

14. There was enough information presented on the HUD to accomplish the NAV task.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	14

Subject 4: 6, No problem except see #12 above

Subject 7: 6, Get good trend information from airspeed needle

Subject 12: 6, This is about the maximum clutter that should be allowed.

15. While using the HUD, I was able to adequately control the required.

Altitude:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	14

Airspeed:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	2	12

Bank Angle:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	4	4	7

Heading:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	2	3	10

Flight Path Angle:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	1	12

Subject 3: Headings were hard to roll-out on - the indicator walks when the aircraft is banked.

Subject 4: Bank angle gets buried under other information easily and gets dropped from instrument crosscheck.

Subject 7: Bank scale is hard to read, not all that useful

Subject 12: Airspeed and altitude analog displays were excellent.

16. The _____ component of the symbology used in the HUD was easy to interpret.

Pitch Ladder:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	3	1	2	8

Bank Scale:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	1	4	3	7

AOA:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	1	1	2	5	4

Flight Path Angle:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	1	12

Airspeed:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	2	13

Altitude:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	2	13

Glideslope:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	2	12

LOC/CDI:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	1	1	0	4	8

Subject 4: Never could figure out how to work the speed worm. Glideslope jumped into view when first introduced to the HUD.

Subject 5: I still don't like the AOA presentation but it is better than the previous one.

Subject 7: The nose up pitch bars are hard to interpret sometimes, especially when in a bank and they are mixed up with the heading scale. For unusual attitude recoveries nose up, ghost horizon is required.

Subject 8: I like having the pitch and bank steering bars rather than one dot to chase.

Subject 9: Pitch ladder - nose high is not real obvious. CDI disappears behind flight director.

Subject 12: LOC/CDI information would get lost in the center of the scope with all other information. Pitch ladder was not intuitive for unusual attitude information.

Subject 13: The acceleration cue was good but obscured by all the clutter

Subject 17: The _____ component of the HUD is placed where it is easy to cross check while performing the ILS task.

Pitch Ladder:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	0	0	1	13

Bank Scale:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	4	1	3	2	5

AOA:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	2	1	1	0	2	8

Flight Path Angle:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	1	1	1	11

Airspeed:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	2	13

Altitude:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	2	13

Glide slope:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	4	11

LOC/CDI:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	1	1	0	0	2	11

Subject 1: Varies slightly based on seating height.

Subject 2: Bank scale - should increase the distance between the scale and the CDM, so that during high AOA maneuvers it doesn't get cluttered.

Subject 4: Bank scale see #16. Glideslope blends in with other information easily

Subject 5: Same AOA comment as #16

Subject 7: Bank scale is so low in field of view on ILS, it's useless.

Subject 8: Very easy once you see it a couple of times

Subject 9: See question #16

Subject 12: Pitch ladder - Remove the 3 deg nose down line. Bank scale - Move it out of the center. AOA - Remove it. Flight path angle - CDM and FPM were excellent. Airspeed and Altitude - Excellent. LOC/CDI - See #16.

Subject 13: Bank scale is fairly useless

Subject 14: With everything lined up, no wind, there is too much stuff at the center of interest.

Subject 15: Bank scale - gets in the way at slow speeds. AOA - useless, get rid of it

18. The _____ component of the HUD is placed where it is easy to cross check while performing the NAV task.

Pitch Ladder:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	14

Bank Scale:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	1	0	4	1	9

Flight Path Angle:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	1	11

Airspeed:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	14

Altitude:

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	1	14

Subject 7: Bank scale is very low, but is it even necessary

Subject 8: There were no AOA, LOC/CDI, glideslope indications and none were necessary

19. While using the HUD rate the resolution of the _____ while performing the ILS task.

Pitch Ladder:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

Bank Scale:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

AOA:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

Flight Path Angle:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

Airspeed:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

Altitude:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

Glideslope:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

LOC/CDI:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	12	2

Subject 4: Glideslope blended in with pitch ladder too easily

Subject 7: Bank scale was not really used

Subject 9: See #15

Subject 10: I would like to see heading to the degree

Subject 15: LOC/CDI - Thicker would be nice

20. While using the HUD rate the resolution of the _____ while performing the NAV task.

Pitch Ladder:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	0	14	0

Bank Scale:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	1	8	0

Flight Path Angle:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	0	12	0

Airspeed:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	0	14	0

Altitude:

	Not Enough	Just Right	Too Much
Rating	1	2	3
# of responses	0	14	0

21. I was able to successfully negotiate the low level portion of the mission using the CDM and tadpole steering cue.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	0	4	10

Subject 8: 6, Very similar to current F-16 symbology. I found it very simple.

Subject 13: 5, Seems like too many symbols

Subject 14: 5, (We're air-to-air only, take this section with a grain of salt)

22. The relationship of the FPM to the CDM enabled me to readily determine an approximate direction and magnitude of the winds on the low level.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	2	3	9

Subject 2: 6, Nicell

Subject 4: 6, Good system

Subject 8: 4, Direction was easy to determine but the simulator made magnitude difficult to assess.

Subject 12: 6, I really liked this function

23. Given sufficient training, I believe I would be able to successfully accomplish the bombing mission.

	Strongly Disagree	Moderately Disagree	Slightly Disagree	Slightly Agree	Moderately Agree	Strongly Agree
Rating	1	2	3	4	5	6
# of responses	0	0	0	1	1	12

Subject 4: 6, No problem using information, altitude marker on radar altimeter needs to be brighter or a different symbol; possibly a >. I couldn't tell what it was supposed to be, it blended in with the tape.

Subject 12: 5, For only the dumb bomb CCIP delivery evaluated.

Subject 14: 4, With sufficient training, anyone could bomb with a manual system

24. Do you envision any conflicts between the HUD symbology, as presented, with any of the missions or mission symbology you are currently flying (YES/NO). If yes, please explain.

Subject 2: No

Subject 3: No

Subject 4: No

Subject 5: No

Subject 6: No

Subject 7: N/A

- Subject 8: Yes, I think the bank scales are unnecessary during air to ground weapons delivery and may clutter the bottom of the HUD. No major conflicts.
- Subject 9: No
- Subject 10: No
- Subject 11: No
- Subject 12: Yes, look at the F-16 and F-15 LANTIRN displays
- Subject 13: Will probably be too cluttered for air-to-air missile employment and air gunnery
- Subject 14: N/A
- Subject 15: No

The three things I like the most about the HUD were:

- Subject 2: (1) Cut down on time of crosscheck due to proximity of info.
(2) Enables the pilot to incorporate outside references when transitioning from instruments to visual flight (ILS D.H.)
- Subject 3: (1) Larger displays of horizon, RALT and glideslope indicator
(2) Bent bar design of below-the-horizon references
(3) Pitch ladder constantly centered
- Subject 4: (1) Correction for wind by the CDM
(2) Bent pitch bars on negative dive angles
(3) Overall layout good for crosscheck
- Subject 5: (1) Flight path information
(2) Grouping and location
(3) Overall ease of use and interpretation
- Subject 6: (1) Position/No head movement
(2) Funnels
(3) Good detailed control
- Subject 7: (1) Vector flying
(2) Airspeed and altitude dials
- Subject 8: (1) Ghost horizon
(2) Different nose low and nose high scales
(3) Pitch and bank steering bars in ILS
- Subject 9: (1) Nice grouping of data - makes cross check more productive
(2) Clock symbol with digits of altitude/airspeed
(3) Bank angle indices
- Subject 10: (1) Quickening/Pitch ladder design
(2) Final approach speed and decision height carrots
(3) Power carrot next to AOA worm
- Subject 11: (1) Ghost Horizon
(2) Funnel effect nose low
(3) Easier cross check
- Subject 12: (1) Precise control of aircraft
(2) Looking out
(3) Airspeed and altitude indications
- Subject 13: (1) Very easy for precise control
(2) All information easily accessible
(3) Vector flying is good
- Subject 14: (1) Ghost Horizon
(2) Climb/dive marker
- Subject 15: (1) Airspeed and altitude gauges vs ladders
(2) Pitch indicator vs waterline

The three things I disliked most about the HUD were:

- Subject 2: No VVI on the HUD (this is a great trend instrument). If you add a VVI, I think a tape type indication would work well.
- Subject 3: (1) A bit cluttered in ILS mode
(2) No target steering with target out of view
(3) Takes a while to correlate the CDM and FPM relationships
- Subject 4: (1) Dot dials around the airspeed and altitude
(2) Size/orientation of numbers and elbows on climbing pitch bars
(3) Compressed scale on pitch bars (good idea, confusing presentation)
- Subject 5: (1) Lack of teepoes on ghost horizon
(2) Dashed and solid pitch lines are harder to interpret than black and white
(3) Lack of VVI information
- Subject 6: Lack of two colors for pitch ladders
- Subject 7: (1) Bank scale - Useless in most situations. When you're at 135 deg bank on the bombing mission you sure aren't looking at a tiny little tick mark to control your bank. You just eyeball a 135 deg relationship between CDM and horizon line.
(2) Conflict between nose-up pitch lines and heading scale
(3) Conflict between bank scale and nose-low pitch lines
- Subject 8: No gun cross. I think this is useful in day to day flying and during weapons delivery
- Subject 9: (1) Limited nose high cues
(2) CDM disappearing to bottom of HUD
(3) HUD is narrow - must lean forward to see all information in field of view.
- Subject 10: Heading display (increments of 5 deg not enough)
- Subject 11: (1) Radar altimeter scale too small
(2) Time/distance to steerpoint hard to see
(3) Bank angle difficult to see
- Subject 12: (1) Hard to establish gross altitude
(2) Too cluttered!
- Subject 13: (1) Too cluttered
(2) Sometimes get confused during UARs
- Subject 14: ILS too cluttered with everything centered
- Subject 15: (1) Indications between above/below horizon
(2) Bank indicator in the way slow speed

Additional Comments:

- Subject 1: The point I am trying to make is that since the HDD is a monochrome display, there is a slight delay in focusing on the display then determining what is seen and interpreting what is seen and then making the right input to correct the unusual attitude. An ADI that is black and white gives that "first look" reliability. The asymmetry of the HUD is good and aids in the unusual attitude determination.
- Subject 4: In the TACAN/Nav mode, move the steerpoint timing and distance up a little in the HUD so that all the information can be seen without having to readjust your head/sitting height
- Subject 7: Lose the 3 deg line on ILS